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High-speed, Low-level Flight: Aircrew Factors

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ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT

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AGARD Conference Proceedings No.267

HIGH-SPEED, LOW-LEVEL FLIGHT: AIRCREW FACTORS

Edited by 10 David

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Papers presented at the Aerospace Medical Panel's Specialists' Meeting held in Lisbon, Portugal, 22–26 October 1979.

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SUMMARY

This volume contains the texts and ensuing discussions of papers presented in Session B of the AGARD Aerospace Medical Panel's 36th Specialists' meeting on 'High-Speed, Low-Level Flight: Aircrew Factors', held in Lisbon, Portugal, from October 24th–26th, 1979. The Session was sponsored by the Biodynamics Sub-Committee of the Aerospace Medical Panel, and included invited contributions from the Flight Mechanics, and Guidance and Control Panels.

The Session, of four half-days, was arranged in five parts, the specific subjects considered in the 28 papers being: Ride Quality and the Effect of the Physical Environment; Thermal Effects, Vibration Effects; Cockpit Design and Aircrew Workload; and Escape and Survival. Particular attention was paid to ride-bumpiness and the influence of airframe design and control strategy, the effects of vibration on vision, and the problems and potential uses of helmet mounted sights and displays.

The Proceedings are completed by the summaries of the five sub-session chairmen; and by the technical evaluation of the organiser and editor.

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TECHNICAL EVALUATION REPORT

by

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The subject of 'High-Speed, Low-Level Flight : Aircrew Factors' was proposed as a topic for a specialists' meeting of the Aerospace Medical Panel of AGARD by the Biodynamics Subcommittee at its annual meeting in Athens in 1976. To quote the theme from the subsequent call for papers: 'Recent developments in radar and missile systems indicate that high-speed flight at low levels offers the optimum means for reaching targets deep within defended territory. Furthermore, the faster and closer to the ground that such flight can reliably be achieved, the greater the chance of mission success. Unfortunately, considerable physical and mental stresses are imposed on the aircrew. The physical stresses are primarily dependent upon speed, height, terrain and atmospheric conditions, but are amenable to modification by aircraft design and control strategy. Aircrew workload may also be reduced by automation and by improvements in system management techniques. Recommendations are needed for current operating systems, for modifications to existing systems and for the design of new systems. It is, therefore, desirable that workers within the compass of Guidance and Control, Flight Mechanics and Aerospace Medicine, should meet to discuss aircrew factors in high-speed, low-level flight, with a view to enhancing the performance of the man and the system and improving the chances of survival of both in this demanding environment'.

Papers were invited on the influence of the physical environment; the effects of high-speed, low-level flight on man; and specific high-speed, low-level aspects of cockpit design, aircrew workload, aircrew equipment, and escape and survival. Review papers were invited through the Guidance and Control and Flight Mechanics Panels of AGARD.

In the event, 28 papers were selected from invited and volunteered abstracts and these fell naturally into five categories. These were : Ride Quality and the Effect of the Physical Environment (four papers including the invited FMP contribution), Thermal Effects (three papers), Vibration Effects (eight papers), Cockpit Design and Aircrew Workload (seven papers including the invited GCP contribution), and Escape and Survival (six papers). A small amount of juggling then produced the required four, half-day sessions allowed for in the timetable for Session B of the 36th Specialists' Meeting of the Aerospace Medical Panel of AGARD. It was held at the Instituto da Defesa Nacional, Calçada das Necessidades No 5, 1300 Lisbon, Portugal, on 24-26 October 1979.

The opening paper in Part I was contributed by Mr J.G. Jones on behalf of the Flight Mechanics Panel and was, to coin a phrase, just what the doctors ordered. It showed the relation between the stress, measured either as the probability distribution or power spectral density of the acceleration response, and the speed, height, terrain and atmospheric conditions; and showed how the stress is affected by aircraft design and control strategy. Thus, 'ride-bumpiness' is dependent upon primary airframe characteristics such as wing loading, lift-curve slope (aspect ratio, leading edge sweep) and speed, and can be accurately predicted (and anticipated). It is essentially intermittent with discrete bumps and poses considerable problems in measurement and simulation. A further factor is the 'vibration' caused by the response of the flexible airframe structure. A figure of 10 Hz is typical for the dominant mode of a small highly manoeuvrable aircraft.

Active control systems can be designed specifically to improve ride-quality, but if employed primarily to improve manoeuvrability, can have the opposite effect. Thus, co-operation between designer and aviation medicine specialist is essential if the optimum overall performance (man plus machine) is to be obtained.

In the next paper (K.R. Krames, B2) it was stressed that meteorological factors are responsible for a significant proportion of severe accidents as well as for variations in aircrew performance. The most important factors are turbulence caused by winds, low level jets, rotors, temperature gradients, and so on, and poor visibility occasioned by dust and salt particles, precipitation, industrial pollutants and insect and bird strikes. Other factors discussed were icing, thunderstorms, sleet and hail, and the contentious question as to whether a pilot's reaction time, *per se*, is affected by meteorological factors. The author concluded that detailed knowledge of all these various factors enables the assignment of flight routes and levels presenting minimum flight hazards, and so reduces the influence of the weather factor in aircraft accidents.

Mr J. Lee then presented a pilot's viewpoint (paper B3) and showed how advances in aircraft design (from Hunter to Tornado) had altered the effects of weather, terrain following flight and aircraft handling. He concluded that great strides had been made, but that areas where further development is required include performance, handling, guidance and navigation, and 'vehicle design characteristics'.

Finally, in Part I, Colonel De Hart discussed the challenges to biotechnology presented by operational high-speed, low-level flight, and illustrated progress being made by films which compared the manually controlled flight of the B-52 with the automated control of the F111 and the low level agility of the A-10 (paper B4). Thus, vibration has become less of a problem and automated systems have earned the confidence of aircrew. However, the specialist in aerospace medicine 'must ensure that sophisticated systems do in fact off load peripheral tasks of the pilot and increase his performance and ability to accomplish successfully the mission in a high threat combat environment'.

Part II consisted of three papers on the thermal problems of high-speed, low-level flight. In these presentations there was considerable consensus that cabin conditioning has not improved in line with other systems, that overheating still poses a considerable problem and that deep body temperatures recorded in current aircraft when flying at high-speed and low-level in warm conditions can cause a reduction in the operational capability of the aircrew. Two of the papers presented fresh evidence that heating decreases performance, the tasks employed being a two-axis pursuit plus reaction time (J. Timbal and J. Colin, paper

B5) and a flight simulator (T.M. Gibson et al, paper B6). These latter authors showed that, for the same deep body temperature, performance is worse during heating than during cooling, and this can lead to drastic errors as well as to less accurate operation of the simulator. In paper B7, R.F. Stribley and S.A. Nunneley made the case for having a physiologically based specification for the environmental control system so that mean skin temperature would be kept below 35°C at all times.

It is apparent that thermal problems will be with us for some time to come and that aircraft designers should raise the priority with which they treat cabin conditioning. Furthermore, air ventilated and liquid cooled suits will still be required under certain conditions, especially in view of the additional thermal load from clothing required for chemical defence and cold-water survival.

In Part III, three quarters of the papers were concerned with the transmission of vibration to the head and the resulting impairment of vision; a not surprising proportion considering the importance of vision to aircrew. L. Vogt et al, (paper B10) described studies in which they had looked at head motion in two axes (Z and X) in response to single axis (Z) whole body vibration. Without a headrest the amplitude of the horizontal vibration component at resonance is about three quarters that of the vertical so that published transmissibility curves for sitting humans by no means represent the complete reactions of the body to vibration stress. These data will be of importance in the formulation of adequate mechanical or mathematical models of the body's response and should stimulate further studies.

In the next paper (M.E. Johnston, B11) the effect of a 'G-tolerant' reclined seat was considered in respect to the transmission of vibration to the head. Head motion increases as the seat back angle to the vertical is increased, and is considerably exacerbated by contact with the headrest. This could pose a problem to comfort and vision and demands further attention, notably the design of a headrest incorporating vibration isolation and the provision of adequate shoulder support to allow the head to be carried comfortably off the headrest.

In the next paper (B12) Dr G.R Barnes looked at the effect of vibration on vision in relation to the pursuit and vestibulo-ocular reflexes. These effects are especially important with the advent of helmet mounted sights since reflex eye movements may then become inappropriate. These and other studies (i.e., papers B13, M.E. Johnston and J.H. Wharf, and B14, N.O. Tatham) provide information for the design of helmet mounted displays - character size, character separation, luminance etc - and suggest that vibration will continue to be a problem in the legibility of all types of display. The third of these papers (B14) showed that laboratory data from subjects exposed to a realistic vibration input gives a good correlation with the accuracy of aiming using helmet mounted sights in real flight. Possible methods for improving aiming accuracy were looked at and one which gives a greater signal to noise ratio by scaling the output of the sight appears effective, though requires the use of an additional display surface rather than a simple reticle. It is clear that much basic research is still needed to perfect a helmet mounted sight system which can be used effectively in high-speed, low-level flight.

Of the other papers in Part III, one (P.Quandieu et al, B8) described basic research on the transmission of vibration in non-human primates and introduced the concept of dynamic mass, whilst a second (J.C. Guignard et al, B9) described a method for studying human biodynamic response to similar Z-axis whole-body vibration. This latter study made use of man-mounted inertial instrumentation and a data reduction technique already established for impact research at the Naval Aerospace Medical Research Laboratory Detachment. The final paper in this part (D.J. Thomas et al, B15) summarised clinical effects which had been noted since 1974 in studies of head and neck response to impact forces. Symptoms and signs, most commonly headaches and neck strain, but also including 11 cases of syncope, had occurred in 625 of 1621 exposures (40%). Despite this wealth of data, 'the transition levels from transient symptoms to injury to permanent damage are unknown'. This information is however, essential for the appropriate design of crash restraint systems.

Part IV, on cockpit design and aircrew workload, opened with the Guidance and Control Panel's contribution (paper B16) in which Morris A. Ostgaard led us from the first flight stabilizer of 1914, through early fly-by-wire systems, to a futuristic cockpit which could provide 'one man, night all-weather low visibility at low altitude'. Whilst this technological progress should have reduced workload by taking over many of the pilot's tasks, workload has actually been maintained by a parallel development from simple vehicle to an 'air warfare system'. The tendency to utilise technology to increase capability rather than reduce workload is understandable, and probably inevitable if optimum overall performance is to be obtained from the man-machine system. However, improved electronic displays should be capable of reducing workload in real terms, especially during high-speed, low-level flight in poor visibility, and this must be a primary design goal.

The next paper (H. Mutschler, B17) considered one feature of an electronic display (in this case a black and white TV), namely the ability of an operator to detect military vehicles in static ground scenes. Factors examined included viewing time, line resolution and contrast, as well as various aspects of the scene. Many of the conclusions are appropriate to cockpit displays, especially to the use of low-light TV. The following two papers were concerned directly with cockpit displays. In the first of these (R.H. Holmes, B18) the design of the display was discussed in relation to workload during high-speed, low-level flight. It was concluded that the pilot should not have to look at essential controls in order to operate them (hence, dedicated controls are still required despite the saving of space offered by the multi-functional approach), and displays should be capable of swift interpretation, both features serving to reduce the time during which vision of the outside world is lost. Arguments were also advanced for making electronic display formats similar to those of their mechanical forbears, and for eliminating unessential information, especially in the area of systems and warnings displays. The second of these papers (D.W. Hussey, B19) discussed in detail the generation of colour displays and their application to reduce workload. Beam indexed colour displays will soon (early 1980s) become available for airborne use. However, colour has to be used sparingly and meaningfully since its indiscriminate use can prove self-defeating.

The last three papers in Part IV were again concerned with helmet mounted displays. It was shown (D.N. Jarrett, Paper B20) that movement of the helmet (and display) relative to the head is less with a realistic vibration input than with voluntary head motion. Also, the degrading effect of vibration can be countered by increasing the luminance of the display. The second paper (G.T. Chisum, B21) discussed the role of such displays in the high-speed, low-level environment in relation to terrain information, threat detection and aircraft information, and highlighted many areas requiring further research. These include what information to offer, what symbology to use, the optimum field of view and brightness, and whether the display should be monocular or binocular. In particular, buffet can make a helmet mounted sight unusable. The final paper in this part (H. Rosenwasser et al, B22) gave a review of programmes of research currently sponsored by the Naval Air Systems Command which are related to visual enhancement. These programmes range from fundamental research on the photo-activation of the retina and the possible use of visually evoked cortical responses to control G-suit inflation, to the use of spectrally selective filters to improve visual performance.

Part V opened with a review of human factors in accidents occurring at high-speed and low level (R.C. Rud and D.F. Leben, B23). The observation that weather is the most influential factor and that in European operations it played a part in 10 of 19 accidents supports the conclusion of paper B2. Low overcast and snow showers are the dominant factors. Not surprisingly, visual problems - white-out, visual illusions - were the most significant human factor demonstrated. Other factors not necessarily specifically relating to high-speed, low-level flight, but more likely to lead to an accident under these flight conditions, are the so-called 'mission completion syndrome', physical fatigue, psychological stress and task overload.

Four of the last five papers were concerned with ejection systems. Paper B24 (G.D. Frisch et al) showed how computor modelling techniques can be used to investigate not only the physical compatability between man and machine, but also reach envelopes and visual fields. In particular, the model has been used to investigate an ejection clearance problem, but it is noteworthy that human acceptance tests were still considered essential in the final analysis. Ejection experience for 1977 had shown that the major causes for fatality were lack of time and altitude, whilst high-speed ejections led to a significant incidence of flail injury (M.A. Hobbs, paper B26). Clearly, improved seat stabilisation and restraint are needed for successful ejection at high-speed and low-level, and a later paper (J.J. Tyburski et al, B28) showed that a vertical seeking seat can offer safe ejection from adverse attitudes, levels as low as 50 feet, and speeds of up to 600 knots. Thus, not only is there a demonstrated need for progress in this area, but systems under development may go some way to offering a solution.

The critical factor of delay between initiation of ejection and aircraft clearance was discussed in paper B27 (J.H. Raddin et al) where it was shown experimentally that torso retraction can be achieved safely in half the 0.3s currently allowed. Furthermore, if the seat back incorporates a sensor and the torso were already in a desirable position, ejection could be immediate. As the delay is only critical in a minority of ejections 'we must take great care to avoid instituting a solution ...... which would compromise safe performance ...... in the majority'.

Only one paper considered the subsequent fate of the successful ejectee. Life support systems typical for tactical jets, patrol and transport aircraft, and helicopters were discussed (W. McIntosh, paper B25), as were the benefits of appropriate training programmes - parachute entanglement, underwater egress etc. A word of caution was voiced that the mass and bulk of survival aids can actually hamper survival and rescue under certain conditions. The US Navy policy is to anticipate recovery within 24 hrs by reducing the amount of this equipment : in fact, 91% of tactical jet ejectees are currently rescued within one hour.

Finally, this evaluation would not be complete without mention of the fine films which accompanied many of the presentations. Whilst they cannot be reproduced in the proceedings, they left an indelible impression on the audience and illustrated, far better than mere words, the meanings of such terms as 'ride-bumpiness' and 'pilot workload'.

CONCLUSIONS AND RECOMMENDATIONS

As noted earlier 'recommendations are needed for current operating systems, for modifications to existing systems, and for the design of new systems'. Whether this meeting can be considered a success depends upon the extent to which these questions can now be answered.

It is clear from the material presented that the major problems currently encountered in high-speed, low-level flight are 'ride-bumpiness', excessive workload and the need for the pilot to divert his attention from the outside view to displays and controls within the cockpit. Ejection also poses a specific problem due to low altitude and often adverse attitude, as does weather, since adequate visibility is essential. Some conclusions and recommendations may be made concerning each of these factors.

1. Ride bumpiness and associated vibration lead to impaired vision, discomfort and fatigue.

   a. To reduce this problem at its source, designers of future aircraft should co-operate with aviation medicine specialists at an early stage in order that airframe characteristics and active control systems can be employed to achieve an optimum compromise between aircraft manoeuvrability and aircrew performance.

   b. To reduce the effect of vibration on the eyes, further research is required into factors affecting head vibration, and into methods for reducing significant frequency components at head level.

   c. To ensure that visual information is still readily available to the pilot, work is needed to optimise display formats, the size and separation of alphanumerics, symbology and the use of colour.

2. The factors already listed would also reduce workload, but the problem of excessive workload should be specifically addressed.

a. Sophisticated electronic systems and displays must be developed with a reduction in workload as a primary aim. Any improvement in mission capability which results from such developments can then be fully utilised by the aircrew.

b. Only essential and appropriate information should be made available to the pilot, but all such information must be provided clearly, without possibility of error, and with minimal distraction from the outside view (see also 1c, above).

3. It is too early to predict the future of helmet mounted sights and displays, but in offering a head-up display which moves with the direction of gaze, they have enormous potential in high-speed, low-level flight.

a. Considerable research is still required into basic visual problems - inappropriate reflexes, binocular rivalry, changing luminance requirements etc., as well as into the design of an optimum display.

b. Vibration poses a particular problem which needs urgent attention if helmet-mounted sights or displays are to be used in high-speed, low-level flight.

4. Weather constitutes an important factor in aircrew performance and accidents, especially in Central Europe. There is an urgent need for visual enhancement techniques (low light TV and infra-red, for example) capable of use "head-up", to give an all-weather and night capability to single seat aircraft.

5. Ejection at high-speed and low-level offers a particular challenge to the designer because all problems are compounded by the need to reduce time delays to the minimum.

a. Restraint systems require further development to reduce flail injuries at speeds greater than 500 knots.

b. Effective stabilisation of the seat is essential, to reduce flail injuries, as well as to allow the operation of vertical seeking devices which could improve the chance of survival following ejection from adverse attitudes.

c. Any re-design of ejection seats required to improve ejection at high-speed and low-level must not compromise ejection safety under other, possibly more common, conditions of flight.

6. The thermal comfort of aircrew is often less than satisfactory in the majority of aircraft types, to the extent that under certain climatic conditions, or when wearing special clothing, performance may be compromised.

a. Designers should raise the priority with which they treat cabin conditioning, giving the aircrew at least as much attention as the electronics.

b. The performance of the environmental control system should be based on physiological requirements, these data being readily available.

D H Glaister

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Wing Commander, RAF
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KEYNOTE ADDRESS

by

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On behalf of the Chief of Staff, Portuguese Air Force, it is my great pleasure to greet the members of the Aerospace Medical Panel on the occasion of its meeting for the second time in Portugal.

It is indeed a great privilege for us to host once again this meeting of leading personalities of NATO in the fields of science and technology relating to aerospace. We hope that your work will be fruitful and, simultaneously, that you will be afforded the opportunity of enjoying some of the natural beauties of my country, and of meeting some of its people whose hospitality and friendliness I always like to emphasize.

The short words of welcome I am honoured to address to you at this opening ceremony have, as a starting point, a brief comment on the circumstances that set the framing for the Portuguese Armed Forces.

Portugal, the oldest state-nation of Europe, is going nowadays through a very difficult period of its already long life as an independent country. At this historical moment, on its shoulders fell, simultaneously, the consequences of a grave crisis in the world economy and the effects of a sudden and disordered withdrawal from territories in the African continent which we have for centuries, colonized, administered, developed, explored and loved.

The unexpected drying up of preferential sources of raw materials and food products, the closing of complementary and privileged markets, and the return of over half a million refugees (just to mention the most important events) were altogether a severe blow for the faint-hearted Portuguese economy, badly shaken already by thirteen years of erosive guerrilla warfare with no military solution. The progressive rise in oil prices worldwide not only hampered the expected economic recovery, but contributed to an aggravation of the situation

As a corollary to this and also -- why not mention it - a certain tendency of the Portuguese people to the anarchic populism, the internal order of the country was badly degraded and, with it, the production output. In parallel, a profound crisis of national identity developed as well, more profound even than the economic and political crisis, which will take a longer time to overcome Confused and disoriented, the Portuguese question themselves about the "collective sense of their destiny", and search for the "accurate definition of their own space among the other nations"

The times we are living in are, therefore, times of crisis political, economical and of national identity

In this national frame, of course, live the Armed Forces.

The effect of the crisis on them is obvious.

During the past stage of greater social instability, the armed forces lived through moments of almost total anarchy, during which they suffered a profound split and were used as a plaything in the hands of the various political groups. It was a rather troubled period resulting from the political inexperience and ingenuousness of the servicemen

However, recovered after having been caught by surprise, when the fundamental values from which they stem naturally emerged again to definitely muffle down the false myths and Utopian demagogism, they managed to free themselves from the mess where blindly and apathetically they had fallen.

Today, all servicemen -- "trustees of tamed violence" -- although aware of the importance of their role in the nation's political life, wish to resume the classic role of watching out for the national security, within the framework of the established democratic rule and in total subordination to the legitimate political power, while responsible for determining the time and place where force shall be used.

I expect that the Portuguese Armed Forces will never again become an instrument of political forces, other than the ones which represent the will of the people and the national interests.

They stand watch for the deceiving mermaids' song, for the seducing false pleas, no matter where they come from, because they shatter the unity so peculiar to the military institution, and indispensable as a solid foundation to its strength.

At this time, I believe one can make applicable to the Portuguese Armed Forces the old popular saying "a burnt child dreads the fire".

In what concerns their operational capability, the Armed Forces are obviously affected by the severe constraints of our economy, and also by a clear anti-military social attitude based mainly on economic but also on political considerations In our particular case, there are still individuals and/or political groups interested in, or determined to foment instability within the Armed Forces, for well-known but not publicly stated reasons Others accuse the Armed Forces of uselessly consuming national resources badly needed in projects of economic development. And there are others who defend, as a matter of convenience, the existence of the Armed Forces, using them as scapegoats to be blamed for anything that goes wrong in the political and economic fields, and also for their own shortcomings and unfitness.

The development of a situation like this, I believe, is by no means exclusive to Portugal Most likely, it took place as well in other countries that lived through periods of similar social turmoil, economic crisis or stages of development

Although the political leadership has thus far, avoided getting involved with the definition of the national defense organization and policy, so to clarify the image and role of the Armed Forces within the Portuguese society of today, mainly because such a definition means assuming responsibility for providing them with the material means necessary to carry the assigned mission, one can nevertheless say that the Portuguese Armed Forces deduced mission is relatively evident, at least on its qualitative aspects.

In so far as the Air Force is concerned, its available resources or the ones it tries to obtain, under the circumstances, represent a minimum requirement for carrying out the tasks which the Portuguese Constitution broadly defines, for fulfilling international commitments, or simply to enable its routine training in order to keep its valuable experience acquired in the operational environment.

Within this line of thinking, the Air Force does not have, at the present, either the capability to operate high-performance aircraft, such as F-16, Mirage 2000 or Tornado, or the hope to acquire it in the short term.

Neither is Portugal politically engaged in any sort of armaments race, nor do we the military people wish to deviate to the armaments field the scarce economic resources, so badly required to satisfy our people's basic needs, through its investment in projects of economic and social development.

On the other hand, we consider it essential to strike a balance between the sophistication of the air assets in our inventory and the technological development of the country, thus recognizing that, to have aircraft of such high performance whose maintenance can't be, to a minimum degree, supported by the national industry, is not of national interest We admit, however, as beneficial, the existence of a certain technological gap to act as a challenge, and to stimulate progress and transfer of "know-how".

The Air Force is, therefore, at this time, orientating its main efforts to the optimization of the human and material resources already available, to the development of the individual capabilities of its men, and to improving its decision-making process.

At the same time, in the technical and scientific fields, it tries to be in touch with the most recently produced technology or scientific breakthroughs.

Therefore, the Portuguese Air Force, although operating an airplane generation obsolete by the standards of the most developed countries, but nevertheless still fit to carry out its mission in the national framework, permanently struggles to keep itself up-to-date with the development and operational use of high-performance airplanes and related problems.

This line of thought justifies our deep interest and great satisfaction in hosting this 36th Panel Business and Specialist Meeting here in Portugal.

Our Air Force medical doctors, who integrate with the NATO Aerospace medical community, will have the opportunity to learn about the operational performances of the most advanced airplanes in being, or projected to be used in Europe, and also about the problems related to the selection, training and required capacity of their crews to carry out missions under heavy mental and physical stress. They will, for sure, broaden their views and understanding of the problems that will affect our crews in the future

Some of our most qualified pilots also have the opportunity of coming to this meeting. Like all pilots they are always eager to fly higher and faster. They will, therefore, have the possibility to listen to the interesting communications you are going to make, according to their proposed titles, and to anticipate some thinking about the problems of the operational use of high-performance airplanes which, some day, they may have the chance to fly themselves. They can start getting adjusted to the restrictions imposed by a heavily hostile environment: flying faster, yes, but definitely much lower.

When the time comes to do it, a solution may have been found for many of today's problems, as a consequence of the studies developed, and the exchange of scientific and technological information, an exchange which is made easier and encouraged by meetings like the one you are going to have here.

From our side, as host nation, we will retain a modest feeling of participation, if not through a direct and productive contribution to the studies to improve performance of men and weapons in an hostile environment, at least through the administrative arrangement of this meeting, through our presence here and our great interest in the subject, and certainly with our most warm welcome to all of you. This feeling of participation is, in its simplicity, useful from a psychological point of view. It gives us the impression of having moved a step forward no matter how little it may be towards the more developed nations of the North, a step that may not be long enough to narrow the gap, but will be big enough to prevent the gap from widening.

I suppose, that, in fact, one can consider your coming to us, within the perspective of the North-South approach.

We all are aware of the disparity between the highly industrialized nations and the less developed countries – the more seriously affected by the world economic crisis and we all know how it tends to aggravate itself and to become a source of tension and conflicts.

Nowadays, in opposition to the until recently dominant way of thinking, the long-term development a strategic objective in every country – is considered to be far more dependent upon cultural, social and political changes than upon a wider availability of material resources

Portugal underwent already and still is undergoing changes of that nature. The respective fruits will be picked eventually, but only in the long term.

In this picture of the Portuguese situation I have tried to draw for you, using colors somewhat covered by heavy shades, the Portuguese Air Force, with the energy and enthusiasm of its youth, keeping itself strongly motivated and internally cohesive. In spite of the difficulties, setbacks and not too good perspectives, the Air Force has found in itself the necessary stamina to develop its operational capacity, bearing in mind that progress is more dependent upon its own initiative than upon outside support.

The Organization of which you are distinguished members is a source of stimulus and I believe it can provide our own human resources with incentive, guidance and support to their endeavours of developing adequate investigation programs, no matter how limited our available means may be.

After all, no matter how big, the available means are always limited.

As I extend to all and each one of you, distinguished representatives of NATO member countries, a specially warm welcome to Lisbon, on behalf of the Chief-of-Staff of the Portuguese Air Force, I also wish that you enjoy your stay in Portugal and after your return to your countries that you may keep a pleasant souvenir of the time you spent with us

RIDE-BUMPINESS AND THE INFLUENCE OF ACTIVE CONTROL SYSTEMS

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SUMMARY

Stresses on aircrew in high-speed low-altitude flight are dependent upon speed, height, terrain and atmospheric conditions, but are amenable to modification by aircraft design and control strategy. As the level of atmospheric turbulence increases, not only does the task of handling the aircraft become more difficult, but the disturbances cause discomfort to the aircrew and make it harder for them to perform control and weapon-aiming tasks. The low-altitude high-speed flight mission is particularly liable to give a rough ride both because there is usually a significant amount of turbulence at low altitude, associated with wind shear in the earth's boundary layer, possibly aggravated by the proximity of rough terrain, and because the magnitude of fluctuations in normal g due to vertical turbulence is directly proportional to aircraft speed.

Various characteristics of aircraft motion which influence ride quality may be distinguished. One is 'ride-bumpiness', related subjectively to gust-induced fluctuations in acceleration and dependent on primary airframe parameters including wing loading, lift-curve slope and speed. Another is 'vibration', mainly due to the response of the flexible airframe structure, in which distinct frequencies of oscillatory motion may perhaps be detectable subjectively at the resonances of the lower-order structural modes.

Active control technology (ACT) permits powerful manipulation of aircraft response to external disturbances as well as to pilot controls. On the one hand advanced control systems may be designed specifically to improve the ride quality. Such systems include ride-smoothing systems for small and relatively rigid aircraft, employing direct-lift control to reduce the amplitude of bumps associated primarily with rigid-body motion, and structural mode control systems for large and relatively flexible aircraft, whose design objectives include the suppression of response in the lower-order structural modes. On the other hand, active control systems designed with some other aspect of performance in view can have an undesirable effect on ride-quality. Such a tendency appears in the case of the aerodynamically-unstable aircraft where the advantages to aircraft performance and manoeuvrability of employing artificial stability are well documented but where the trends in gust response tend to be adverse.

Standard methods for assessing ride-quality are briefly reviewed. In addition, a relatively new technique is described that combines time-plane characteristics of response with frequency-plane features usually defined in terms of power-spectra. This method, which has been developed as a tool for assessing the dynamic response of aircraft in turbulence, may provide useful additional information for human factors work. The technique leads in particular to a 'characteristic signature', in the time plane, of the aircraft response to gusts. In determining the dependence on aircraft dynamics of this characteristic energy pattern emphasis is placed on the concept of signal 'increments' or 'differences', in contrast to the sinusoidal components of Fourier analysis. It is perhaps relevant that the role of signal differences in time or space is also stressed in classical work on the mechanisms of human sensory perception.

1 INTRODUCTION

High speed aircraft frequently operate at very low altitudes, navigating over long distances, using terrain-following or other techniques, to locate targets precisely and deliver their weapons with a high probability of striking the target on the first pass. Low-level operations must be relatively free from the adverse effects of turbulence, gust loadings and manoeuvre restrictions, the aircraft must retain its characteristics as a stable weapons platform and pilot fatigue in the low altitude regime must be minimal[1].

The operational efficiency of the crew during flight in a low-level gust environment is dependent on a number of factors[2]:

(a) atmospheric turbulence structure and levels

(b) the characteristics of the aircraft in responding to turbulence, including the effects of structural modes

(c) the tolerance of the crew to the level and duration of the bumpiness and vibration at the crew station.

The quantification and relation of these features depends on an analytical description of the aircraft motion. Statistical measures of aircraft motion that have been

traditionally regarded as relevant to ride-quality assessment may be separated into two distinct classes:

(i) measures based on probability distributions for the amplitude of acceleration response peaks

(ii) measures based on frequency-dependent or power-spectral properties of acceleration response.

To these should be added the influence of aircraft pitching motion which has a measurable effect on pilot workload through its influence on the assessment of the aircraft as a stable weapons-platform.

Measures of type (i) above have usually been expressed in terms[3] of '½ g bumps per minute'. This type of criterion has been applied in particular in the context of high-speed flight of relatively rigid aircraft and is largely dependent on aircraft whole-body motion. To assess aircraft response in this form some form of discrete-gust turbulence model is usually employed. In recent applications of this approach, statistical families of discrete gusts have been used to represent patches of 'continuous' turbulence and theoretical predictions for the rate-of-occurrence of bumps of arbitrary amplitude (and not just ½-g bumps) deduced[4], see Fig 1.

Measures of type (ii) above, based upon frequency-dependent or power-spectral properties, are widely used at the present time. Standard turbulence models are available (eg in MIL-F-8785B) in the form of power spectral densities of either 'Von Karman' or 'Dryden' form, from which various measures of response may be deduced. These include the power spectral density of response, the normalised rms load factor[5] $\bar{A}$, which is based upon the area under the spectral-density curve, and a Crew Sensitivity Index for ride quality[6] that weights the response spectral-density with a function that expresses human tolerance as a function of frequency.

The influence of primary airframe parameters including the wing loading W/S, the lift-curve slope C_{L_α} and speed V may be deduced from either a discrete-gust or a power-spectral approach. In the former case the 'tuned response' (ie response to tuned gust or critical gust pattern) is given by[4]

$$\bar{\gamma} \sim V\left(\frac{\rho S C_{L_\alpha}}{2W}\right)^{2/3} , \qquad (1)$$

a relation that contains, in the $\frac{2}{3}$-power, the dependence of gust amplitude on wavelength. In the latter the rms load factor is given by[5]

$$\bar{A} \sim \frac{\rho V S C_{L_\alpha}}{2W} \sqrt{\frac{I(k,s)}{\Pi}} , \qquad (2)$$

where the term I (k,s) incorporates the effects of the turbulence spectrum.

Equations (1) and (2) may be shown to be essentially equivalent. The dominant factors at a given flight condition are the wing loading and the lift curve slope. The latter is strongly influenced by the aspect ratio and the leading-edge sweep. Figures 1 and 2 (from Refs 4 and 5) illustrate these effects.

The ride quality is further aggravated by the influence of the structural mode response to gusts. Typical of fighter-aircraft gust response[5] are the data shown in Fig 3, obtained from flight tests on a relatively small highly-manoeuvrable aircraft and showing the contribution of the first body bending mode to the overall power spectral density of the gust response at the pilot station. The frequency of the dominant mode of flexible response may be seen to be at 10 Hz. This contrasts strongly with data[7] for a large and relatively flexible aircraft, designed to fly in close proximity to the terrain at high speeds, where spectra of longitudinal response show marked peaks at approximately 3 Hz and 7 Hz with lateral response modes appearing in the same range.

It is characteristic of aircraft flexible-mode response that its time history is markedly oscillatory or quasi-sinusoidal, in contrast with bumpiness associated with whole-body motion, which is essentially intermittent with discrete bumps often distinguishable in relative isolation. This qualitative distinction may be expected to be significant for aircrew performance and subjective impression and should be reflected both in analytical criteria for ride quality and in the motion of ground-based simulators. We will return to this topic subsequently.

Although we have concentrated on the influence of normal acceleration on ride quality, effects of aircraft pitching motion need also to be taken into account. The direct effect of angular motion upon smoothness of ride is probably considerably less than that of normal acceleration from the point of view of aircrew capability and efficiency. However, in the context of combat aircraft, where the quality of the aircraft as a platform for weapon release is of prime importance, the effects of gust-induced pitch disturbances on weapon accuracy and associated pilot workload are of major concern.

A central topic of this paper is the influence of active control technology (ACT) on aircraft ride characteristics. As a preliminary, however, we briefly review the available methods for assessing such influence in quantitative terms.

2 TOOLS FOR THE ASSESSMENT OF AIRCRAFT RIDE CHARACTERISTICS

The most widely-used methods for the assessment of ride quality involve frequency-dependent or power-spectral density (PSD) characteristics of response. The evaluation of ride quality in these terms is illustrated in Fig 4. There are three main components[7]. The gust power spectral density is a measure of the excitation energy in the atmosphere as a function of the wave number (inverse of wavelength) Ω; once the speed of the aircraft is defined the wavenumber can be viewed as a frequency parameter ($\Omega = \omega/V$). The second component is the frequency response of normal acceleration (normal load factor) at the crew station due to unit amplitude sinusoidal vertical gusts. Relating this to the gust power spectral density curve it can be seen (Fig 4) that the energy in the atmosphere can excite the rigid-body (whole vehicle) motion and a number of the lower frequency structural modes. The third component takes the form of a weighting of the response motion at various frequencies, depending on the dynamic response characteristics of the human body. As shown at the bottom of Fig 4, all of these data are brought together into $\bar{H}_z$, a Crew Sensitivity Index for Ride Quality. If the 'human frequency response' T_D were left out of the calculation, the rms load factor $\bar{A}$ would be obtained. $\bar{A}$ is sometimes preferred[5] to $\bar{H}_z$ as an indicator of ride quality because it permits direct correlation with various forms of analysis including comparison with simulator results. A typical analytical result in this form has already been given, equation (2).

A lateral parameter $\bar{H}_y$ is developed similarly to $\bar{H}_z$ with the gust spectrum remaining the same, but with lateral aircraft frequency response and the human response function reflecting different characteristics.

The levels of $\bar{H}_z$ and $\bar{H}_y$ accepted as design criteria are influenced by a number of factors, including mission time; these are discussed and evaluated against response characteristics of a number of typical military aircraft in Ref 6.

Since the 'human frequency response' element of this method (Fig 4) is largely based on measured human response to sinusoidal motions, the appropriate applications of measures of this type arise in situations dominated by response of a highly oscillatory character. In qualitative terms the motion then takes the form of relatively continuous vibration as in the response to structural modes rather than irregular or intermittent sequences of individual bumps. We take the view that the use of data based on quasi-sinusoidal vibration to treat aircraft whole-body ride bumpiness in turbulence is a suspect procedure.

For the treatment of discrete fluctuations in normal acceleration, or 'bumps', an alternative framework exists[4,8] comprising a turbulence model in which families of discrete gusts are used to represent patches of continuous turbulence. In this statistical discrete gust (SDG) method, the turbulence model takes the form of an aggregate of discrete ramp gusts which, for the assessment of aircraft rigid-body response, are considered either singly (Fig 5) or in pairs (Fig 6). Families of 'equiprobable' ramp gusts follow a law $v_m \sim H^{1/3}$ as illustrated in Fig 7. These statistical characteristics are consistent with the energy distribution defined in standard forms of the power-spectrum turbulence model (von Karman spectrum). It is thus possible to employ coordinated discrete-gust and power-spectral turbulence models, both related to a common turbulence reference intensity $\bar{\sigma}$ which acts as an overall measure of atmospheric disturbances and for which probabilities of exceedance are available based on overall global statistics (see Appendix B of Ref 8 and also Ref 9). The relationship between the reference intensity $\bar{\sigma}$ and the true rms intensity $\bar{\sigma}_i$ of a component of turbulence with scale length L is illustrated in terms of power spectra in Fig 8. Turbulence intensity is often described qualitatively as light, severe, etc. Such terms may be approximately related to specific values of the reference intensity according to the following table:

Grades of turbulence and reference intensities

Nominal grade of turbulence	Values of reference intensity	
	m/s	f/s
Light	0.9	3
Moderate	1.8	6
Severe	3.7	12

The discrete-gust analysis of aircraft response takes place in the time plane and involves a search over families of equiprobable gust patterns, including both isolated gusts and gust-pairs, for the 'tuned gust' or 'tuned gust pattern' which produces the maximum or 'worst' response. The theoretical prediction for the rate-of-occurrence of bumps then takes the form[8]

$$n_y = n_o \exp\left\{-\frac{y}{\beta\bar{\gamma}}\right\}, \tag{3}$$

where

$$n_o = \alpha/\lambda\bar{H} \tag{4}$$

and n_y is the average number, per unit distance flown, of aircraft normal acceleration peaks with magnitude greater than an arbitrary magnitude y

α, β are parameters which define the statistical properties of the patch of turbulence through which the aircraft is flying (see below)

$\bar{H}$ is the tuned (or critical) gust length (not to be confused with Crew Sensitivity Indices $\bar{H}_z$ and $\bar{H}_y$)

$\bar{\gamma}$ is the tuned response (response to tuned gust or critical gust pattern)

λ is the gust length sensitivity.

The tuned response $\bar{\gamma}$ may be associated with either a single isolated gust or with a gust-pair combination; the precise condition is

$$\bar{\gamma} = \max \begin{cases} \bar{\gamma}_1 \\ 0.85\ \bar{\gamma}_2 \end{cases}$$

where $\bar{\gamma}_1$ and $\bar{\gamma}_2$ are respectively the maximum response to a single isolated ramp gust (Fig 5) and the maximum resonant response to a pair of gusts (Fig 6), and the individual component gusts are chosen from the same (equiprobable) family (Fig 7).

The statistical result given by equations (3) and (4) may be supplemented by the evaluation of the quantity

$$\bar{T} = \bar{H}/V\ , \tag{5}$$

which is strictly a measure of the time taken to traverse a tuned-gust gradient distance $\bar{H}$ but may also be used as an approximation to the rise time to peak amplitude of the associated response. Equivalently $\bar{T}$ may be regarded as an approximate measure of the 'duration' of the response peak. In particular, in the case of normal acceleration response, $\bar{T}$ may be related to the 'sharpness' of the bump. A generalisation of this approach to incorporate the complete 'characteristic signature' of the bump is described in Section 4.

For the purpose of ride-quality assessment for low-altitude high-speed flight it is proposed in Ref 8 that nominal patch lengths of 5 miles (8 km) be assumed, an overall mission being regarded as a sequence of such patches with varying turbulence intensity from patch to patch. It should be emphasised that the assumption of 5 mile patch lengths is an over-simplified and provisional representation of the patchiness properties of real atmospheric turbulence. In fact, intense patches can sometimes be very short, describable as a burst or cluster of gusts. However, despite its limitations, the nominal patchiness postulated is believed to be adequate as a basis for the analytical comparison of the ride characteristics of differing aircraft configurations. In terms of the assumption of 5 mile patch lengths, the provisional statistical model proposed in Ref 8 takes the form

$$\alpha = 0.38 \text{ (dimensionless)}$$

$$\beta = \begin{cases} 0.07\ \bar{\sigma} & \text{(f/s units)} \\ 0.10\ \bar{\sigma} & \text{(m/s units)} \end{cases}$$

where α, β appear in equations (3) and (4) and $\bar{\sigma}$ is the turbulence reference intensity[9] (Fig 8).

3 THE INFLUENCE OF ACTIVE CONTROL SYSTEMS

3.1 Preliminary remarks

The benefits of Active Control Technology (ACT) for both fighter aircraft designed for combat and for large flexible aircraft designed to fly in close proximity to the terrain at high speeds and for long periods have been well documented[7,10].

In the case of combat aircraft[10], the benefits include weight reduction, performance and handling improvements. Very significant improvements in performance can be achieved with artificial longitudinal stability coupled with automatic operations of combat flaps. The adoption of spin prevention and automatic manoeuvre limiting will give 'care free' manoeuvring. In addition, improvements in aircraft ride-bumpiness characteristics may in principle be achieved by the use of ride-smoothing systems employing direct-lift-control[4,5], although it should be pointed out that the benefits may not in all cases justify the cost and complexity of such a system[10].

In the case of large flexible aircraft, there is a requirement to provide a specified level of ride quality for the crew. This requirement has been met on the B-1 aircraft[7] through the use of an automatic control system called a structural mode control system (SMCS) whose main external feature is a set of vanes near the nose of the aircraft. A substantial saving in weight was achieved[7] with this approach as compared with the direct alternative of material stiffening of the structure.

Not all changes in aircraft response associated with ACT are necessarily beneficial, however. In particular, the improvement in aircraft manoeuvrability by the use of

artificial longitudinal stability tends to be associated with a degradation in the response of the aircraft to turbulence (although this, in turn, may be alleviated by the addition of a ride-smoothing system).

In the following sections we illustrate some of these trends by means of particular examples.

3.2 Ride-smoothing system employing direct lift control (DLC)

Earlier results of this paper have confirmed (Figs 1 and 2) that high wing loading and low lift-curve slope contribute to good longitudinal ride qualities. However, the choice of such airframe characteristics generally has to be a compromise between the requirements for ride and the requirements for manoeuvrability. A possible course in this situation is to choose (low) values of wing loading and (high) values of lift slope primarily to achieve good manoeuvrability and to attempt to recover adequate ride qualities by means of a ride-smoothing system. In the following we compare the changes in ride characteristics that may be achieved in this manner[11] with analogous improvements that would result from an increase of the airframe parameter $(W/S)/C_{L_\alpha}$.

The type of gust-alleviation system considered in this section is aimed to reduce ride-bumpiness associated with rigid-body response and the discussion is particularly relevant to relatively rigid aircraft (with natural response as in Fig 3, for example). We defer to Section 3.3 the discussion of active control systems whose primary objective is to alleviate vibration associated with the response of the flexible structure.

In Ref 4 two alternative types of closed-loop control were discussed, one employing normal-acceleration feedback and the other incidence feedback, in each case to a DLC motivator such as a wing flap surface. In addition to the DLC loop, each system had a pitch stabilisation loop which employed pitch-rate feedback to an elevator or tailplane motivator.

Typical results are illustrated in Fig 9 where the effects of basic airframe changes and of an active ride-smoothing system are contrasted. In terms of the parameters in equations (3), (4) and (5) the following trends occur

	increasing $\frac{W/S}{C_{L_\alpha}}$	addition of ride-smoothing system
$\bar{\gamma}$	decreases	decreases
n_o	decreases	increases
$\bar{T}$	increases	decreases

Thus, whilst the effect of increasing $(W/S)/C_{L_\alpha}$ is to decrease both the amplitude of bumps, as measured by $\bar{\gamma}$, and their total number, as measured by the 'zero crossing parameter' n_o, the effect of the ride-smoothing system is to decrease $\bar{\gamma}$ but to increase n_o.

It thus appears that the improvements in ride quality obtainable using a ride-smoothing system tends to be dissimilar in character from the improvements due to increasing $(W/S)/C_{L_\alpha}$, for example by increasing wing sweep, with which pilots are familiar.

Analogous results may be obtained[11] using the power-spectral approach, where an equivalent 'zero-crossing parameter' is given by

$$n_o = \sigma_{\dddot{h}}/\sigma_{\ddot{h}} \qquad (6)$$

and $\sigma_{\dddot{h}}$, $\sigma_{\ddot{h}}$ are the rms rate-of-change of acceleration and the rms acceleration respectively. On the other hand such features are not encompassed explicitly by the Crew Sensitivity Index, Fig 4. We draw the conclusion that further work on the human factors aspects is required to determine the extent to which increasing n_o (and decreasing $\bar{T}$) is a genuine detrimental effect.

The above trends may be illustrated, Fig 10, by means of extracts from computer-simulated time histories[4]. These show that the theoretical trends need to be interpreted with some care. The decrease in bump amplitude associated with the ride-smoothing system is clearly apparent. On the other hand the associated increase in n_o, and decrease in $\bar{T}$, may be seen to be due simply to the removal of low-frequency components of the fluctuations whilst the higher-frequency content remains relatively unaltered. As a result, the removal of energy has caused an increase in the rate of sign reversal of the time history of incremental load factor. In the case of increased $(W/S)/C_{L_\alpha}$ the bumps are distinctly softer-edged (Fig 10). The significance of this phenomenon is underlined by the fact that cases have been reported where pilots have remarked on a 'cobblestone ride' in an aircraft with a ride-smoothing system. Moreover, the computer simulation illustrated in Fig 10

was based on rigid-body equations of motion. With structural flexibility included, the relative sharpness of the bumps in the case of Fig 10b would probably be accentuated.

3.3 Structural mode control system (SMCS)

The following material has been obtained from the description of the B-1 ride control system presented in Ref 7.

One of the principal missions of the B-1 involved flying for long periods of time close to the terrain. The design requirements produced a relatively flexible aircraft. This vehicle flexibility, combined with the ever-present low-altitude atmospheric turbulence, could have produced an acceleration environment at the crew station which could degrade general crew efficiency with a consequent hazard to mission success.

The B-1 design employs a variable sweep wing which is swept aft when flying the low-altitude mission. The aft-swept wing has a low lift-curve slope and thus is less susceptible to turbulence excitation loads. Despite sweeping the wing the response to turbulence in the structural-response modes was still too high to meet the ride-quality requirements. Two basic design choices remained: (1) add material (and weight) to stiffen the structure over that needed for strength and flutter requirements, or (2) use an active control system to control the lower structural modes, up to 10 Hz. The latter approach led to significant weight savings. The active control implementation was the so-called ILAF (identical location of accelerometer and force) concept, previously evaluated during the flight test research programme on the XB-70, and incorporates suppression of both vertical and lateral bending motion.

The Von Karman gust power spectral density curve was used in calculations of the ride quality (crew sensitivity indices, $\bar{H}_z$ and $\bar{H}_y$) and the rms accelerations due to turbulence, $\bar{A}_z$ and $\bar{A}_y$.

Crew sensitivity index data are shown in Fig 11. Data are shown for the basic aircraft, the SCAS (stability and control augmentation system) operating, and the SCAS + SMCS operating. The peak at low frequency is the short-period (rigid-body) response and the large structural response at about 18 rad/sec frequency is a mode consisting primarily of fuselage bending.

As can be seen (Fig 11), the SCAS does its intended job of damping the short-period motion, but slightly excites the structural response. The operation of the SMCS substantially reduces the structural motion, whilst not interfering with the short period, and demonstrates a capability for meeting the specification $\bar{H}_z$ (specification level was $\bar{H}_z < 0.028$). Similar results for the lateral modes of structural response are presented in Ref 7.

Effects of operating the SMCS are illustrated[7] by means of time-history plots in Fig 12. The data were recorded in a flight during which considerable light-to-moderate turbulence was present nearly continuously. In both vertical and lateral motions the effect of operating the SMCS is to reduce the amplitudes significantly. Moreover, in the case of vertical motion the quality of the response may be seen to be changed, by the increase in damping, from being a highly oscillatory vibration to a more irregular sequence of fluctuations not dissimilar (in this particular run) to the bumpiness already shown, Fig 10, to be characteristic of a much smaller and relatively-rigid combat aircraft.

3.4 Artificial longitudinal stability

In an aircraft not fitted with a feedback control system, longitudinal stability must be obtained by having the neutral point behind the centre of gravity. This implies in practice that the tail provides a downward force, or negative lift, with consequent penalties in drag.

An active control system can profoundly alter this, for by feeding back control signals to the elevators (or tailplane) to provide suitable pitching moment the longitudinal stability characteristics can be completely changed. In particular, it is no longer necessary to insist that the centre of gravity lies ahead of the neutral point.

The improvements in aircraft performance achievable in this manner have been well documented elsewhere[10]. The case for relaxed aerodynamic stability is now widely accepted and its practical implementation hinges only on the safety, reliability and cost of the active control system required to provide the necessary degree of overall flight stability.

However, the successful implementation of control laws involves not only stability but also the broader spectrum of what are generally called 'flying qualities'. Flying qualities not only involve stability and transient response to pilot's control, which is the principal concern of much of the studies published on active control, but such matters as gust response, behaviour near and beyond the stall, steady manoeuvring characteristics and even control and stability during the ground roll. For any active control system to be acceptable it must of course maintain in all these areas the standards we demand of the conventional aircraft. Shortcomings, even if they manifest themselves only at the periphery of the flight and manoeuvre envelope, must be identified and means devised for their correction.

A review of these topics has recently been presented in Ref 12, where the conclusion is drawn that whilst currently-designed systems appear to be capable of satisfying the main objective of providing at least short-period stability of the relevant aircraft modes they all fall short in some way of satisfying all the handling requirements. In particular, response to vertical gusts tends to be significantly amplified with the use of pitch-rate based feedbacks.

We illustrate these points by comparing the response to vertical gusts of aircraft which have positive, neutral and negative longitudinal aerodynamic stability respectively.

Figs 13 and 14 show the response to vertical gusts of aircraft with stabilizing terms involving pitch-rate and integral pitch-rate feedback. The results are based on power-spectral-density (PSD) analysis. In each case it can be seen that, in moving from the naturally-stable to the unstable aircraft there is a significant increase in response at the lower frequencies.

Such results are confirmed by a statistical discrete-gust (SDG) analysis. In this method, as outlined in Section 2, the response amplitude is measured in terms of the 'tuned response' $\bar{y}$ ie the 'worst case' response, of maximum amplitude, corresponding to a prescribed family of equiprobable gusts (such a family generalises the traditional concept of a 'design gust'). $\bar{y}$ may be associated with a particular time history, or 'tuned response pattern' which corresponds to the worst-case gust and which may be shown to characterize the gust response of the system in question even when the excitation is due to continuous turbulence (see Section 4).

Fig 15a compares the tuned-response patterns for the normal-acceleration response of stable and unstable aircraft to vertical gusts. It may be seen that, in moving from the naturally stable to the unstable aircraft, there is both a significant increase in the amplitude of response and a decrease in the dominant frequency, consistent with the trends predicted[12] by the PSD analysis.

A further interesting result, obtained from the SDG analysis, concerns the characteristic gust-induced pitching motion. The tuned-response patterns for the naturally stable and unstable aircraft are compared in Fig 15b. Not only is the response considerably slowed down in the case of the unstable aircraft, the characteristic time history extending over a longer period, but the initial direction of response may be seen to be in the opposite sense. This is due to the initial response of the aircraft being dominated by the (negative) aerodynamic stability; only after some pitch rate has developed does this particular control system apply control moments in the sense of (overall) positive stability.

We are here, of course, not implying any inherent and irremedial deficiencies associated with the implementation of control laws for the case of relaxed aerodynamic stability. The point being made is that the implementation process requires much more than a simple consideration of stability questions. A full consideration of flying qualities requires the careful investigation of transient responses to both pilot demands and to external disturbances such as gusts. We should not be surprised to find flying characteristics that differ considerably from those to today's aircraft and which will require careful assessment by pilots. This conclusion is somewhat reminiscent of that reached in the context of ride-smoothing systems (Section 3.2) and draws attention to the fact that traditional design requirements for aircraft flying qualities and ride qualities are based on experience with a restricted class of dynamic response characteristics that is rapidly becoming outdated.

4 SIGNAL STRUCTURE AND RIDE-QUALITY ASSESSMENT

In Section 2 we reviewed the tools available for assessing aircraft ride quality in turbulence. It will be apparent that there is more than one way of approaching the problem of signal analysis and synthesis for theoretical or simulation purposes. In this final section we take a look at some of the basic issues that have arisen through studies of aircraft flight dynamics but that appear to have direct relevance to the human factors specialist.

We will denote the turbulence input or forcing function (generally the vertical component of turbulence velocity) by v(t) and the aircraft response (which will generally be normal acceleration at the crew station but may also be, for example, pitch rate) by y(t). A major concern in the study of ride-bumpiness is then the occurrence and structure of the larger peaks in y(t). In terms of a Fourier decomposition into sinusoidal components, such peaks occur whenever the components of differing frequencies reinforce one another. This phenomenon may be likened to the concept of 'interference' in optics, where it is well known that if two sinusoidal patterns of differing frequencies are superposed, there result some regions of 'constructive interference', where the amplitudes of the waves add together, and other regions where they tend to cancel one another. A region where constructive interference arises may be thought of as a local energy concentration.

In the power spectral density (PSD) method, see Section 2, different Fourier components are assumed to be statistically uncorrelated and the occurrence of such wave reinforcement is assumed to take place on a purely random, or chance, basis. This assumption leads to a particular relation, based on the 'normal' or 'Gaussian' distribution, between the amplitude of a large peak value of y(t) and the local rms value σ_y (evaluated over a 'patch' within which the turbulence is assumed to have stationary statistical characteristics). On the other hand, the basis of the statistical discrete-gust (SDG) method is that large peaks in aircraft response, associated with wave reinforcement, in fact occur with

increased probability on account of phase correlations between Fourier components of different frequency. Theoretically, these occur as a result of nonlinear terms in the equations of fluid mechanics. Physically, they take the form of 'ordered structures' in the turbulent flow field and may be interpreted as intermittently-occurring concentrations of energy. The SDG model introduces such energy concentrations explicitly in the form of discrete ramp gusts.

The mathematical background of the PSD method is the so-called theory of continuous random processes. The study of localised regions of energy concentration, as in the SDG method, follows on the other hand from a quite distinct mathematical background. The original work is due to Gabor[13] and has been particularly fruitful in the area of acoustic signal decomposition and synthesis and the study of sensory processes[14]. The basic result concerns a constraint on the nature of regions of constructive interference (corresponding to energy concentration) between sinusoidal components covering a range of frequencies Δf. This is the 'uncertainty relation' which states that if a 'packet' of waves covering the frequency range Δf reinforce one another over an interval of time Δt, and cancel elsewhere, then the product $\Delta f.\ \Delta t$ has a minimal possible value, of order unity. An element (Δf, Δt) in the 'time/frequency diagram' which takes this minimum value was called by Gabor a 'logon'.

The relation of this work to the SDG method is that the ramp gust profile, illustrated in Fig 5, may be shown to satisfy the minimum area condition on the product $\Delta f.\ \Delta t$, where Δt is simply the duration of the gust $\Delta t = H/V$ as seen by an aircraft travelling with speed V. In Ref 13 Gabor showed how an arbitrary signal could be expressed as a sum of such elementary signals (logons).

Thus the ramp-gust profile, or 'smooth increment', qualifies as a possible basis for representing arbitrary gust patterns. Moreover, from the point of view of reproducing those features of a gust pattern that relate to the existence of a large peak in aircraft response, there is evidence that the ramp profile is the most efficient signal element in the sense of requiring the minimum number of significant elements per pattern (and is much more efficient than a sinusoidal or Fourier component for instance). Simple examples of gust patterns synthesised in this manner, together with their representations in the time/frequency plane, are illustrated in Fig 16. Note that these patterns include both sequences of ramps (Fig 16(a) and (b)) and also the superposition of short ramps on top of longer ones (Fig 16(c)). Each of the patterns illustrated in Fig 16 has in fact been shown in recent work to be derivable as the 'tuned gust pattern' of some dynamical system characteristic of aircraft response (the tuned gust pattern being the input producing the most critical system response, see Section 2). Fig 16(a) illustrates a gust pair, comprising sequential ramps of opposite sign, with the first gust of the pair having rather greater length, or gradient distance, than the second. Such a profile is characteristic, for example, of the tuned gust pattern for aircraft normal acceleration response to the vertical component of turbulence when the aircraft pitch damping is sufficiently low[8]. It should be noted that the 'energy elements' in the time/frequency plane (Fig 16) have been assigned appropriate positive and negative signs, corresponding to positive and negative increments in the time history. Fig 16(b) illustrates a similar pattern, comprising increments of alternating sign, but with four ramp components. Such a profile is characteristic, for example, of the tuned gust pattern for normal acceleration at the crew station associated with a not-too-well damped fuselage bending mode (see Fig 12). Fig 16(c) illustrates a pattern comprising superposed ramps of the same sign but having significantly differing gradient distances (such that the corresponding elements in the time/frequency plane are non-overlapping). Tuned gust patterns of this form have been found in recent studies[4,11] of the response of an aircraft with a ride-smoothing system employing direct lift control (Section 3.2). With sufficient autostabilisation in pitch, the basic aircraft longitudinal response has a tuned gust pattern comprising a single ramp. The introduction of the 'DLC loop', however, adds a higher-frequency mode such that, at a sufficiently large value of the gain, the tuned gust pattern takes the form illustrated in Fig 16(c). For intermediate gains the tuned pattern comprises a single ramp of intermediate gradient distance.

Thus the SDG method leads to an explicit study of 'gust patterns' and their mathematical representation. In addition, for some applications there is equal interest in the nature of the region of wave reinforcement (or energy concentration) is the associated response function y(t). For instance, in the study of ride bumpiness, the SDG method leads to an associated 'tuned response pattern', or 'characteristic signature' of the response in the neighbourhood of a large peak value (see Fig 15). Indeed, such a characteristic signature, which may take the form of a single well-damped fluctuation or may be markedly oscillatory, may be said to characterize the 'bump'. In recent studies (to be published) the theoretical tuned response pattern, derived in this manner, has been shown to match very well the ensemble average of samples of time histories of response to measured continuous turbulence, where the samples each contain a large peak and are scaled and phased so that the peak values are superposed. Thus, whilst the individual time histories of response in the vicinity of a large peak do contain some random element, it has been confirmed that there is also a predictable common underlying pattern.

We referred above to the fact that the ramp profile (Fig 5), or smooth increment, is an economical signal element in the sense of requiring the minimum number of elements to represent the significant features of a gust pattern. This is somewhat reminiscent of the manner in which the central nervous system (of animals and humans) interprets sensations in terms of input patterns whose basic ingredients are <u>differences</u> (see Part II of Ref 15 or the section 'Form, substance and difference' of Ref 16, for example). It is perhaps not too far-fetched to regard the structure of an aircraft as an extension of the pilot's nervous system and the physical sensation associated with a typical 'bump' on that aircraft

as the recognition of a particular input pattern in the environment. By means of the 'tuned response pattern' evaluated as outlined above we may go on to study the 'texture' of that sensation and the manner in which it relates to behaviour such as the simultaneous performance of tasks (effect on workload).

In this context, the manner in which the characteristic response patterns 'stand out' from background noise is of importance. For instance, ground-based simulators that employ conventional Gaussian-noise generators to simulate the turbulence environment are criticised by pilots as being 'too predictable' or 'lacking the occasional large bumps', even though they may reproduce the correct power-spectral characteristics. The point here is that Gaussian noise is essentially 'structureless' or ' featureless', irrespective of the form of the power spectrum. In generating appropriate signals for simulators it is necessary to accommodate the relevant non-Gaussian features.

One way of achieving this, developed at RAE Bedford, is based on the generation of random sequences of elementary discrete ramp profiles with statistical characteristics as described in Section 2. Details of this synthesis technique, in which a software algorithm is implemented on a digital computer and used to produce, in real time, a continuous 'turbulence' record for aircraft handling qualities studies in a piloted ground-based simulator, have been presented in Ref 17. The method has recently been further developed for use at NLR as described in Ref 18. However, the 'discrete gust' method is not the only way to approach the problem of generating a non-Gaussian signal as a model of atmospheric turbulence for real-time simulators. Comparable success has been achieved using a technique originally developed by Reeves[19], in which the multiplication of two independent Gaussian random signals was the basic approach used to generate each of three orthogonal gust components. More recently, this approach has been taken as the basis for further work on the modelling of turbulence for simulation purposes at Delft University of Technology, the Netherlands, of which a report by Van de Moesdijk[20] is the most recent example, describing a development which shows promise as a means of generating a random signal with non-Gaussian increments.

For the future, we suggest that both power-spectral and discrete-gust approaches to the modelling of turbulence are here to stay and that each type of model may be related to specific aspects of ride-quality, as outlined in Section 2. Turbulence is a complex process involving the interplay of randomness on the one hand and order or structure on the other. This is reflected in the use of random process theory on the one hand and the representation of specific signal patterns on the other. The results of recent work suggest that in the field of signal synthesis the products of the two methods may be converging (for instance, both methods are currently capable of generating signals with fairly realistic 'patchiness' characteristics). It is, of course, a healthy situation that the protagonists of the alternative approaches are as firmly entrenched in their respective positions as ever. My own preference follows the common-sense view of the philosopher A N Whitehead, who in 'The Aims of Education' commented 'We perceive things in space. For example, among such things are dogs, chairs, curtains, drops of water, gusts of air, ...'.

However the element of 'structure' is introduced into a fluctuating signal, whether by the multiplication of Gaussian random processes or by the introduction of explicit signal patterns, it is clearly an important aspect of ride quality as perceived by aircrew. In the past, ride-smoothing systems have generally been linear systems designed to a mean-square error criterion. A possible alternative lies in the use of nonlinear systems[21], designed specifically for non-Gaussian inputs, whose objective is to remove the non-Gaussian structure of the output. A quantitative approach along these lines has in fact been proposed by Weidemann[22] who advocates the use of error entropy rather than mean-square error amplitude as a measure of system performance. The output of such a system would ideally be a broad-band Gaussian process and thus essentially structureless. Perhaps here lies a pointer to a future generation of ride-smoothing active control systems.

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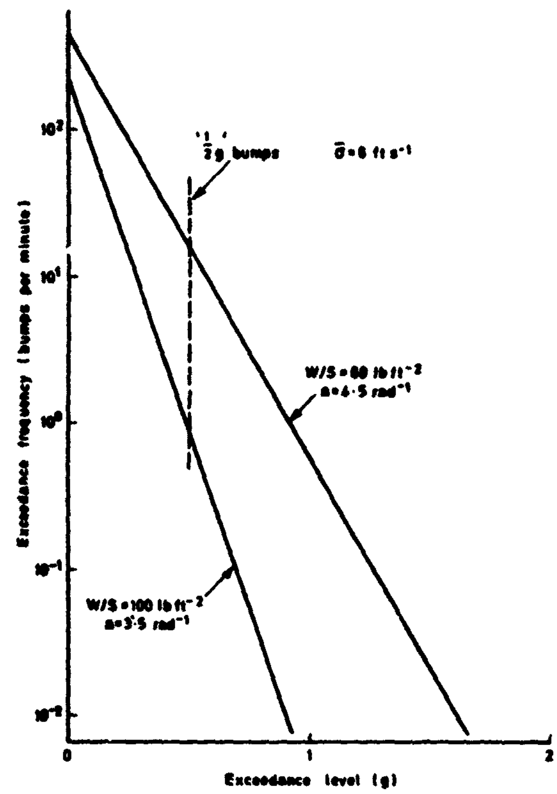


Fig 1 Influence of wing loading and lift slope on aggregate of positive and negative bumps in moderate turbulence at low altitude, M = 0.7 (from Ref 4).

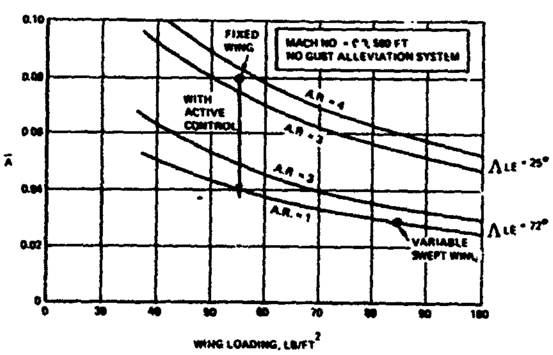


Fig 2 Effect of aircraft parameters on $\bar{A}$ (from Ref 5).

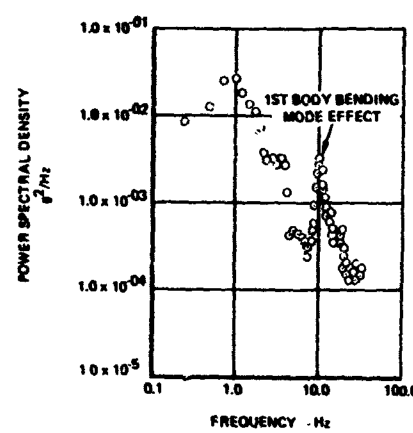
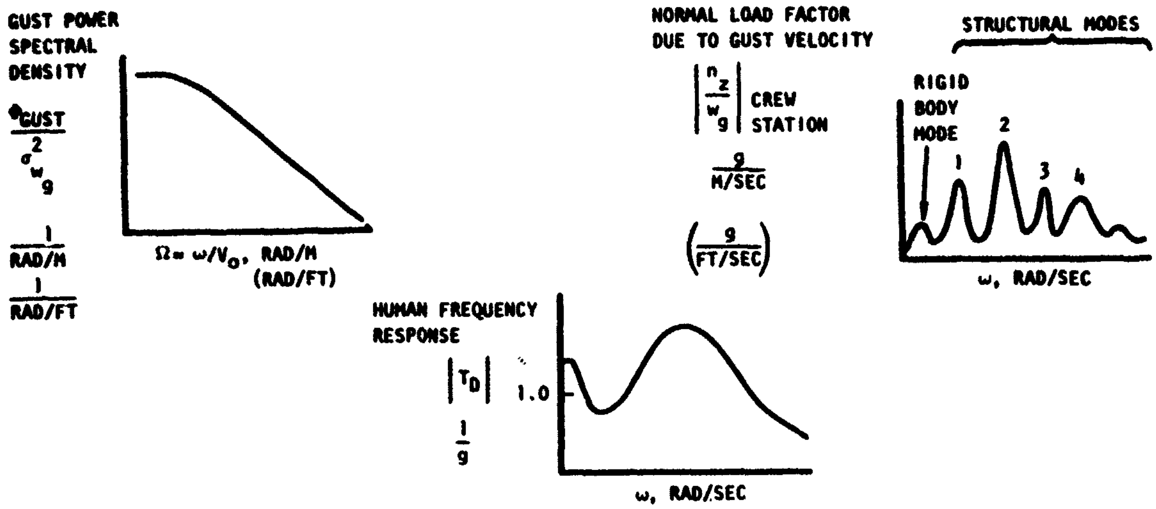


Fig 3 Power spectral density for a highly manoeuvrable fighter aircraft (from Ref 5).



$$\bar{H}_Z = \left[\int_0^\infty |T_D|^2 \left|\frac{n_z}{w_g}\right|^2 \frac{\Phi_{GUST}}{\sigma^2_{w_g}} \, d\omega\right]^{\frac{1}{2}} \frac{1}{M/SEC} \left(\frac{1}{FT/SEC}\right)$$

Fig 4 Crew Sensitivity Index for Ride Quality (from Ref 7).

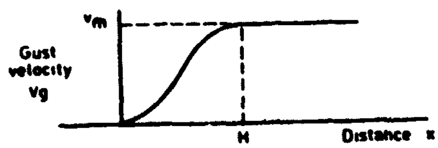


Fig 5 Smooth ramp gust (from Ref 4).

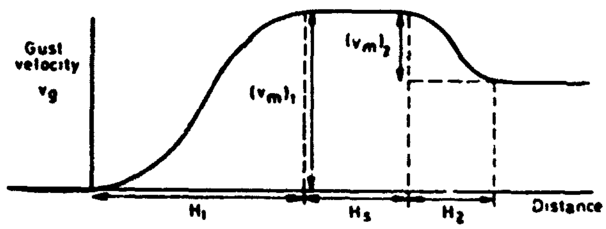


Fig 6 Pair of ramp gusts (from Ref 4).

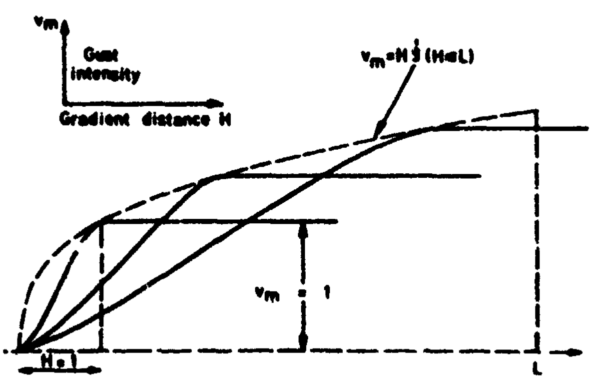


Fig 7 Family of equiprobable ramp gusts (from Ref 4).

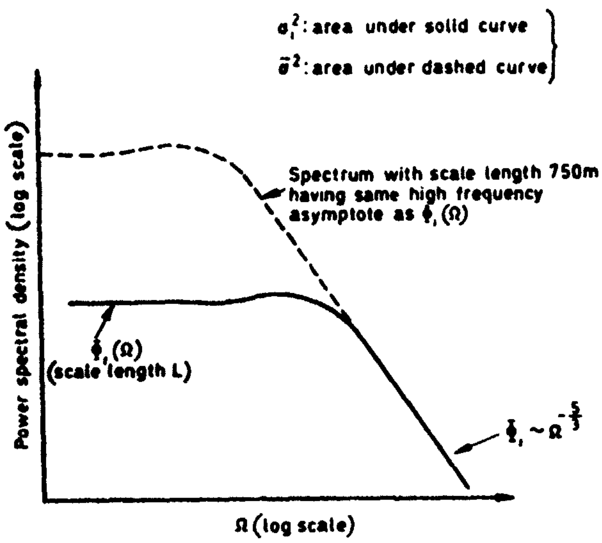
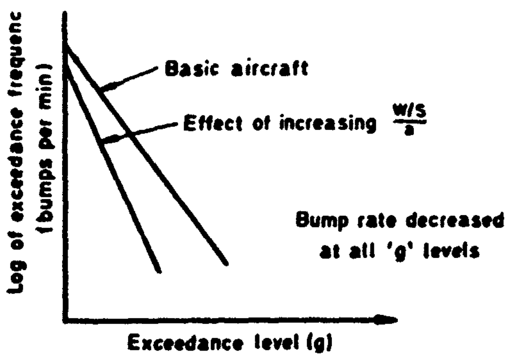
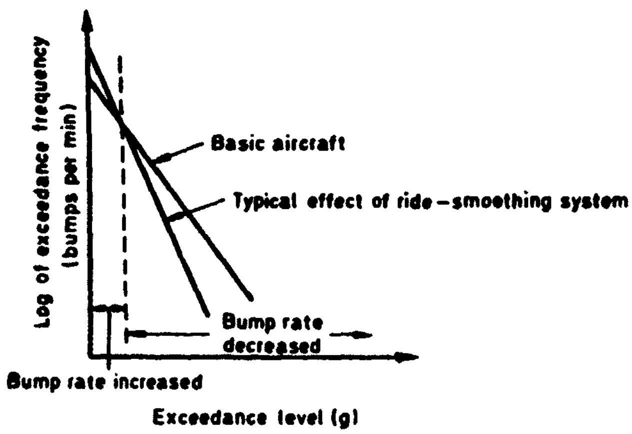


Fig 8 Relationship between power spectral density and Reference Intensity $\bar{\sigma}$ (from Ref 4).

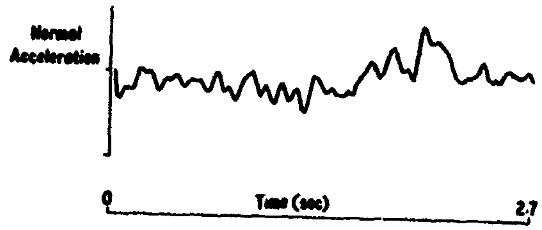


a Effect of basic airframe change

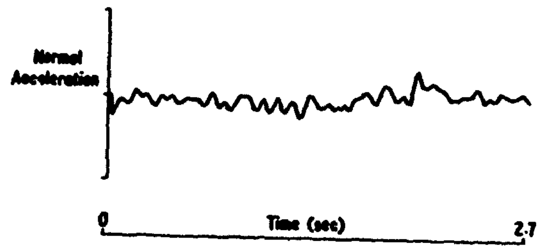


b Typical effect of ride-smoothing system

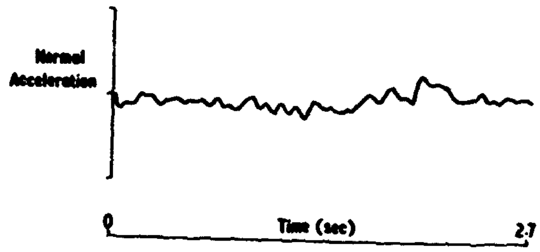
Fig 9 Contrast between effects of basic airframe changes and of active riue-smoothing system (from Ref 4).



Simulated time history of response of basic aircraft



Simulated time history of response with ride smoothing system $(B_{\ddot{h}} = 20)$



Simulated time history of response with $\frac{W/S}{a}$ increased by a factor of 2.14

Fig 10 Contrasting effects on time histories (from Ref 4).

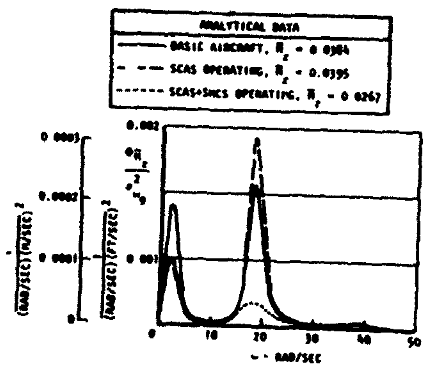


Fig 11 Power spectral densities associated with Vertical Crew Sensitivity Index, $\bar{H}_z$, M = 0.85, altitude 2,500 ft (from Ref 7).

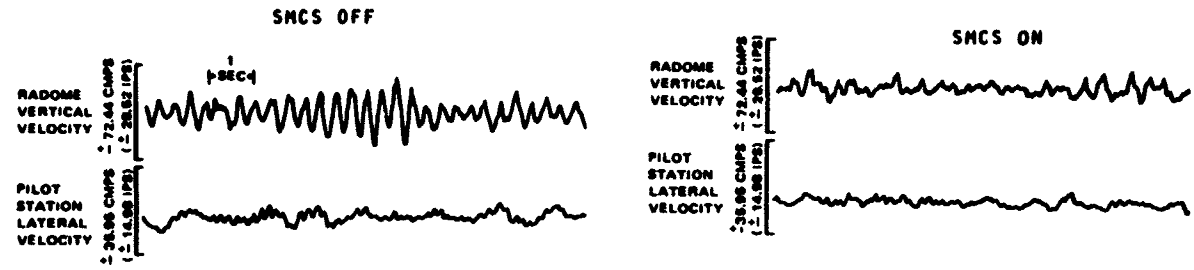


Fig 12 SMCS performance in turbulence
M = 0.70, altitude 1,000 ft
(from Ref 7).

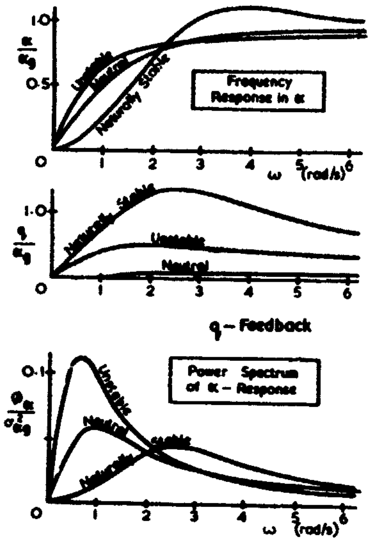


Fig 13 Contrasting turbulence response
of naturally-stable aircraft and unstable aircraft
with pitch-rate feedback
(from Ref 12).

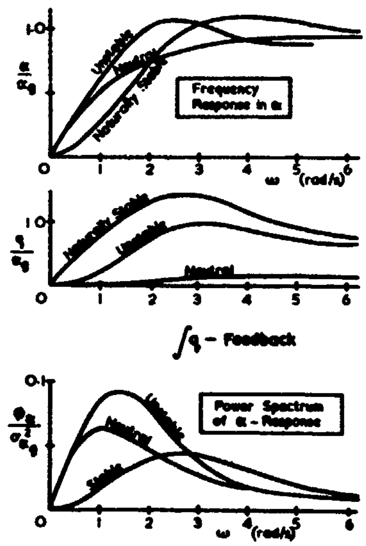


Fig 14 Contrasting turbulence response
of naturally-stable aircraft and unstable aircraft
with integral-pitch-rate feedback
(from Ref 12).

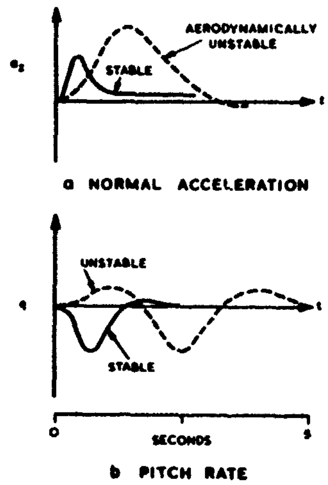


Fig 15 Tuned response patterns
(statistical discrete gust theory)

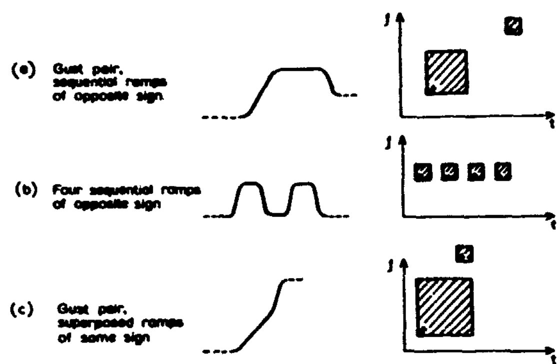


Fig 16 Tuned gust patterns and
related time/frequency diagrams.

INFLUENCES OF GEOPHYSICAL FACTORS (METEOROLOGICAL AND TOPOGRAPHICAL) ON THE PILOT-AIRCRAFT-SYSTEM IN HIGH SPEED LOW LEVEL FLIGHT (HSLLF)

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SUMMARY

Low level flights are conducted in areas of strong interaction between atmosphere, lithosphere, hydrosphere, and biosphere. This means that there is an ever growing number of geophysical flight hazards encountered in high speed low level flight. Therefore, stringent demands are placed on the reaction capability of the man-machine-system.

As early as 1941, meteorologists established proof of man's faster reaction to acoustic signals than to optical signals. This fact, only recently verified by human engineers, also has significant impact on cockpit design in modern day aircraft construction.

The primary function of geophysical information consists in assessing those flight routes and flight levels presenting minimum potential hazards to the accomplishment of the individual military mission. The use of terrain data bases - like the Federal Armed Forces' topographic data base - offers an optimal approach in achieving a high degree of resolution on the basis of 95-by-150-m-grids. The inclusion of weather, vegetation, and surface data will ensure detailed flight information. In Germany it may be hoped to maintain the low rate of flight accidents due to weather factors.

1. GENERAL PROBLEMS

The development of the modern anti-aircraft technology forces the construction of still faster and more maneuverable aircraft that can operate as close to the ground as possible. In discussions on the cost-effectiveness of such expensive weapon systems graphical representations like those shown in Fig. 1 are frequently presented. They demonstrate the correlation of increasing survivability with lower flight levels.

However, such reflections are only valid for models which do not take the influence of the atmosphere into account and whose (terrain) relief energy has to be dimensioned in such a way that terrain-following at high speed is still possible. Also they require such a degree of perfection of the integrated man-machine-system that the impacts of the general geophysics discussed in the following sections are not allowed to cause any disturbance on the reaction procedure at its most sensitive point - the signal receiving and order-giving human brain. Here, very special medico-meteorological problems are touched for which solutions have to be found.

It needs to be emphasized that realistic presentations of the earth's terrain features must also consider the mechanisms of various atmospheric influences, particularly when LLF is involved. The American approach, stating that there are "numerous examples in war history telling that the consideration and utilization of certain weather advantages" resulted in "a bigger chance for the victory" /1/, is absolutely valid.

The "Yom-Kippur-War" should stand as an example for the crucial importance of visibility conditions in determining the time of starting an offensive. This problem will be discussed later.

If one considers that the temporal and local heterogeneity of the surface weather is substantially more pronounced in midlatitudes than in subtropical latitudes one must conclude that the optimal preparation and performance of any defensive system in this region is strongly dependent on the consideration of geophysical influences.

The above-mentioned variability of the geophysical factors may upset the man-machine-system to such a degree that flight accidents result in critical situations.

It is worth mentioning that recent evaluations of flight accidents in Austrian civil aviation (published in 1978), show 14 % of the severe accidents during the period of 1966 - 1976 caused by meteorological impacts /2/. The most serious negative influences are the following:

Wind (turbulence)	96 Accidents
Visibility	37 Accidents
Icing	5 Accidents
Hail	2 Accidents
Medico-Meteorological Phenomena	2 Accidents
Lightning strike	1 Accident

Without asking for the reasons for the significantly lower contribution of weather factors to aviation accidents within the German "Bundeswehr" it should be pointed out that the "geofactor" might become increasingly important in the military domaine again, if LLF are performed without precise geophysical support, Fig. 2.

This support of course requires the detailed knowledge of the meteorological phenomena in the surface layer of the atmosphere. Therefore the aviation meteorologist often has to make use of research methods commonly used by agricultural meteorologists. This especially relates to problems dealing with visibilities in a realistic battle-field atmosphere which are substantially dependent on the lithometeors, because different kinds of soil are able to produce very different stability conditions in the lowest friction layer.

If one simultaneously considers that the air layer near the ground can contain biological or chemical warfare agents it is evident that questions concerning visibility get an additional ophthalmological aspect, and therefore cannot be answered without the assistance of an aviation medical expert.

The participation of an ophthalmologist in investigations of incidents during the twilight and night hours seems to be necessary, in order to consider the individual eyesight when determining a pilot's range of detection in comparison with that of a co-pilot aquipped with a light intensifier or night goggles. For a rough estimation of the visual aids which have just been mentioned it might be sufficient that such experiments are performed with normal-sighted persons /3/. The results thus obtained are undoubtedly relevant only for slow-flying aircraft, especially helicopters which are able to hover over one point for a longer period of time to detect an object.

The target detection from low level fast flying aircraft with a high angular velocity, however, is expected to be restricted during the dark; mainly because of adaptation problems which become quite pressing near the ground because brightness can vary considerably.

A close cooperation between pilot, doctor, and geophysicist becomes urgently necessary, in order to answer such extremely complex questions.

Some difficult medico-meteorological questions will be discussed later. At first the author will give a general view on the geophysical hazards any pilot aircraft system in the low level flight is exposed to.

2. GEOPHYSICAL FACTORS IN THE LOWER FRICTION LAYER OF THE ATMOSPHERE

2.1 General Remarks

The English as well as the German professional literature is now using the term "boundary-layer" for that part of the lower troposphere highly influenced by frictional effects of the earth's surface. Its thickness is approximately 500 m over open water, and about 1 000 m over land. Large variations from these values may occur depending on the roughness of sea and especially land surfaces. Besides this the height of the boundary layer is subject to diurnal and seasonal variations.

For the solution of interaction problems between the atmosphere and the lithosphere it is important to note that the lower limit of the atmosphere is not identical with the upper limit of the lithosphere. Depending on the porosity and the permeability of rocks the atmosphere can penetrate to different depths causing weathering as it is well known. Fine grained rocky fragments can then be whirled up by frictional forces of the atmosphere and consequently interfere with atmospheric processes in initiating condensation for instance.

Pointing out these "atmosphere-lithosphere interaction phenomena" is so essential because they characterize the battle-field atmosphere in the case of defence due to additional warfare effects.

Similar conditions occur over the sea because of the interaction between the atmosphere and the hydrosphere within the friction layer. The chloride aerosols represent ideal condensation nuclei. Depending on the circulation conditions they can be transported far into the land where they endanger the LLF in certain weather situations which will be discussed in a later section.

The interaction between atmosphere, lithosphere, and hydrosphere is caused by frictional forces. Hence preference is given to the term "friction layer" instead of "boundary-layer".

By the way, the intensive interaction between all three spheres has caused the formation of the biosphere which is highly active in the friction layer. For that reason increasing risks caused by the biosphere must be expected with increasing low level flights.

The mathematical treatmen of hazards such as

- increasing possibility of shoot-downs in the HLF due to hostile firing,
- increasing danger of crashes because of the complex geophysical effects in the LLF,

requires still more intensive and detailed geophysical support which will be possible only by use of computers because of the numerous factors that have to be considered, for instance, those touching the domaine of medico-meteorology.

The solution of the survival problem of a pilot-aircraft system in any case of conflict will, therefore, not be

- The use of the lowest FL, but
- The calculation of the optimal FL on a most favorable flight-route by use of extensive data material.

2.2 Visibility

For VFR flights exact visibility forecasts play a major role for the successful accomplishment of the military mission. One has to distinguish between the meteorological visibility reported by the observer on the surface and the in-flight and slant visibility observed by the pilot. The latter frequently differs considerably from the meteorological visibility because of the heterogeneity of the geophysical factors which reduce the visibility. Moreover, in LLF the horizon is determined primarily by the relief forming a maximum visual range. In the following section this visibility is denoted as "topographic visibility".

2.2.1 Topographic Visibility

The topographic visibility gives the exact distance of the maximum possible observability of a field from a fixed point. It is a priori clear that the topographic visibility must have different values

- in the different lines of sight, and
- in the different flight levels.

The value of the topographic visibility which is only defined by the morphology can be assumed to be quasi-constant. It certainly can be influenced by extensive natural or artificial changes in topographical features. However, if cultivation and vegetation is taken into account temporal changes of topographic data have to be considered.

A comparison of figures 3 and 4 shows that, for the given terrain example, the vegetation can not be disregarded when making an exact topographic visibility statement /4/.

It is also fundamental for terrain types of moderate relief energy that the horizontal visibility considerably decreases with the approach to the surface. See Fig. 5, 6, 7.

It has to be emphasized here that the topographic visibility can be reduced by geophysical effects so that due to the meteorological visibility of the observer as well as the in-flight visibility of the pilot the VFR-flight can be rendered difficult or even impossible in spite of favourable terrain conditions. This is why the terrain data inevitably have to be supplemented by geophysical data. These do not only refer to the meteorological visibility, but also to other parameters which under certain circumstances can obstruct a LLF. This subject will be treated in the following sections.

2.2.2 Meteorological Visibility and In-Flight Visibility

Because of the interaction of the atmosphere with the earth's surface, decomposed materials incessantly emerge into the atmosphere from which they are sedimented mostly at other places due to general circulation and compensation. As figure 8 shows the troposphere and above all the friction layer contain dust or lithometeors /5/.

In sparsely vegetated areas, especially within the subtropics, soil heating connected with unhindered insolation causes extremely strong instability in the lowest friction layer so that intensive interaction phenomena like dust and sandstorms frequently occur here.

Satellite pictures have shown how large the areas are in which such conditions prevail. For example, at Crete, Sahara dust is observed on an average of 15 times a year causing considerable visibility reduction /6/. In this context it may be recalled that, due to the effect described, a British naval force was able to operate off Crete undetected by German reconnaissance flights during a decisive phase of World War II.

Of still greater influence on a military operation was the reduction of visibility by lithometeors at the Syrian front on the outset of the Yom Kippur War. The time of attack was originally favourably scheduled for sunrise, and later postponed to 1400 hours by the Egyptian Commander in Chief, General Ismail; as a consequence the Syrians had to begin their operation at a time of maximum instability, i.e. at the time of the highest degree of lithometeoric saturation in the friction layer. This forced the Syrians not only to look into the sun, but at the same time also to have extremely poor reconnaissance conditions so that according to the French General Beaufre, the Israelians succeeded in destroying a major portion of the Syrian tanks in a quick countermove /7/.

Conversely, after geophysical consultation, the Israelians had scheduled H-hour of the Six-Days-War in the morning (0830) for best visibility conditions. Minimum turbulence, present at the same time, enabled them to bombard precisely all Egyptian air bases so that the enemy air force was wiped out in almost no time /8/.

But due to certain geological conditions also in mid-latitudes, for instance, in the drift-sand areas of the "Emsland" (NW Germany) the visibility can be deteriorated to such an extent as to obstruct the terrestrial navigation for the pilot. Such conditions occur to a great extent in areas where pronounced sources of lithometeors arise from industrialization after the removal of the vegetational cover. Examples are open-pit coal mines and quarries. Because of these lithometeors, the flight operations at nearby air bases, such as Noervenich, near the soft coal mining region of the "Ville", or Mendig in the margin of the cinder-block production area of the "Neuwieder-Basin", can be disturbed drastically.

Actually all man made or biological contaminants of the atmosphere along with all kinds of aerosols, i.e. all of the solid emissions of settlements as well as industrial and agricultural production areas, belong to the lithometeors in a meteorological sense. They frequently represent ideal condensation nuclei due to their high hygroscopicity. Pre-condensation, mainly caused by sulphuric pollutants, frequently starts at a relative humidity of only 70 %, rapidly reducing visibility as humidity increases. VFR can then become a problem especially over largely urbanized and industrialized terrain.

It is so important to regard these man made aerosols because the experience of the last wars has shown that considerable aerosol concentrations causing visibility reductions in the LLF have to be expected from mass employment of various weapons under certain weather situations.

The results of aircraft ascents of several years prior to the 2nd World War in Germany and the simultaneous meteorological observations (mostly twice a day) have confirmed a high dust concentration in the layer below the surface inversion which reacts as a kind of barrier for lithometeors.

This large-scale investigation by the former weather reconnaissance flights revealed a surprising uniformity of the top of the dust layer on the average for all weather situations. Therefore it was right that this very exact observation material from different stations was comprehensively evaluated in the research of the vertical structure of the hydrometeors by Möller, de Bary et al.

Finally, the author felt free to compare the dust observations of Vienna, Norderney, Königsberg, etc. with the inversion heights calculated from English weather reconnaissance flights over Stornoway, Liverpool, Leuchars, Lerwick, Larkhill, Downham Market, Comborne, and Aldergrove. Figure 9 shows with striking clearness how the temperature inversion acts as a barrier for the dust layer below.

It is important for the LLF problems discussed here that in-flight measurements conducted in Germany revealed that the lower limits of nearly all dust layers are identical with the earth's surface. There are only a few cases with a suspended dust layer where underflying might be possible. The presentations of the upper limits of dust include the frequencies of dust layer thickness. The high degree of conformity of both curves indirectly demonstrates that the lower limit of the dust layer coincides with the upper limit of the lithosphere.

This does of course not mean that the vertical distribution of aerosol particles remains constant. Generally one can confidently expect the aerosol-density to increase towards the top of the inversion layer. At this height the visibility for the pilot is therefore most unfavourable.

During the 2nd World War, the strong horizontal continuity of the dust layer was verified by H. Berg using aircraft ascents /9/. He emphatically called attention to the decrease in visibility over industrial regions in weather situations with inversions. The in-flight or slant visibility may drop below 1 km even when relatively good meteorological visibilities are reported from the observation site on the ground making surface orientation impossible. Some fatal flight-incidents occured on the German side under such conditions. Once it even led to an erroneous landing on enemy territory.

Figure 10 gives a general view of the influence of dust on visibility.

The degree to which the probably most intensive man made environmental disturbance - the war - affects interactions between atmosphere, lithosphere, and biosphere was shown during the Berlin bomb-raids between 1943 and 1944. The measurements presented in figure 11 demonstrate an additional dust content of up to 300 % for the years just mentioned.

This point is stressed because the importance of realistic battlefield atmosphere is not always realized for the assessment of the operational capability of new weapon systems. The estimation of in-flight visibility for LLF is completely unrealistic if this is done on the basis of a standard atmosphere.

A lot of money has therefore been spent by the British in field experiments aiming solely at the measurement of the transmissivity of a battle-field atmosphere in different spectral ranges /10, 11/. Hereby the absorption due to dust, chemical warfare agents, and artificial fog is also investigated.

To what extent the coincidence of all previously listed components at their maximum efficiency in the upper haze-layer may inflict upon a pilot's health, disregarding the visibility obstructions, is a question that has to be answered by physicians.

From the geophysical side it shall only be pointed out once more that hazelayers are favourable heights for hydrometeors as a result of their supply of ideal condensation nuclei. This easily explains the vertical structure of cloud formation found by Berg, Skierlo, Möller, de Bary et al. shown in Fig. 12. The frequent occurrance of low clouds is very characteristic for large portions of Europe. Especially the fog types, which Dove rightly calles "clouds on the ground floor", are considered as being essential for a judgment of visibility obstructions due to hydrometeors in the low level.

The precipitation resulting from these "clouds" also causes severe visibility obstructions in the lower friction layer. This is especially valid for the winter months when in connection with the low freezing layer the amount of snow in the net precipitation is large. In summer the higher flight levels may offer somewhat less favourable visibility conditions because of the larger portion of snow at these altitudes.

The higher amounts of precipitation recorded in mountainous regions are, however, by no means representative for the corresponding levels in the free atmosphere. The increase in snow fall and rainfall in high altitudes is the result of the orographic lifting of air masses and the consequential increase in condensation. In low level flights these areas must be avoided if current geophysical informations call for it.

Heavy precipitation and the resulting erosion of the front edges of wings, intakes, pressure tubes, brake flaps, infrared-windows, and radomes in HSLLF can create critical flight conditions /12/.

The reference to the different effects of precipitation could be supplemented with respect to the PGW-communication and orientation systems installed on board. This is, therefore, a typical example for the fact that only one weather component can affect different parts of a complicated weapon system in various ways so that under certain circumstances the cumulative effect may produce critical flight conditions.

For this reason icing in HSLLF should be discussed in this chapter even though it not only affects the in-flight visibility as a result of ice-accretion on the cockpit windows. The different aerodynamical heating of various aircraft types and their components cause different icing risks which of course must be considered for HS aircraft.

It is fundamentally valid for all aircraft that the icing risk is less at temperatures very much below 0° C than at temperatures in the range of 0° C to - 10° C, Fig. 13.

In mid-latitudes, especially in the cold season, the risk of icing in the LLF must increase due to the fact that in the lower layer the amount of available supercooled water is higher because of a higher frequency of clouds.

It must be emphasized in this context that the dangerous freezing rain is a typical winter phenomenon when cold air at the surface is overrun by warm air. The increase in the number of low level flights without proper geophysical support, therefore, must result in an increased icing risk.

The icing risk in the lower friction layer becomes even more critical since aircraft with ice accretion are more affected by the strongly varying horizontal and vertical winds/13/.

Visibility problems with low flights over the sea are most frequent in connection with glazy sea. The main criterion for this is a wave height $<$ 0.5 m. Such low wave heights are the result of distinct stability categories and wind speeds in the lower friction layer. Generally one of the following conditions is necessary:

- Unstable stratification, i.e. cold air over warm water;
  calm winds
- Stable stratification, i.e. warm air over cold water;
  wind speed $\leq$ 6 kt
- Strong stable stratification;
  wind speed $\leq$ 10 kt
- Extremely stable stratification;
  wind speed $\leq$ 20 kt

Following this it is quite possible that glazy sea can occur even with a relatively high wind speed (5-6 Beaufort), for example, in the case of strongly heated continental air advection over a cool water surface. Then this warm air is lying over a shallow layer of cold air filled with mist from evaporation so that the pilot can barely realize the transition between water and air.

When higher wind speeds destroy the film of cold air and cause sea spray an aircraft in HSLLF may be covered by a saltfilm which under certain circumstances reduces engine performance and in-flight visibility. Insidious corrosion can also cause critical flight situations.

In this context it should be emphasised that salt accretion is by no means restricted to aircraft operating in maritime areas. French geophysicists found that F A T A C aircraft crossing eastern France in low-level flights had several times actually been covered by a mouse-grey salt-layer. Following Chappaz e.g. a "significant salt-layer" formed on the aircraft of group 2/13 which operated in LLF on 16 Nov 77 in the area Nancy - Neufchâteau, far away from the sea /14, 15, 16/.

According to the analyses of weather maps for the cases observed to date only the Atlantic Ocean or the North Sea can be assumed to be the source of this salt.

Following Chappaz the conditions for salt accretion are the following:

- Flights at high speed
- Low flight levels
- High windspeed over the sea with spray formation
- High instability
- Low lying inversions
- On-Shore flow patterns in the lower air layer.

For practical use these criteria imply that particularly during winter where high instability in the lower friction layer over the open water is created by the advection of very cold air from polar and arctic regions, a chloride concentration below a marked inversion is produced and the salt particles are transported over long distances in o the continent and effect aircraft in the LLF.

As Chappaz for France, W. Fett and H. Ceyp have reported of saltsedimentation on aircraft in England and Germany /17, 18/. H. Ceyp remarked that the salt particles are not necessarily of maritime origine. As possible land-bound sources he considered dumps of Salt or potash mines.

In dry areas, as for example Algeria salt-domes which penetrate the surface can emit salt particles into the air, this is of course also valid for salt-lakes and man made salt gardens. Therefore W. Fett also mentions some extreme cases in the USA., where actual salt storms originating in the Salt Lake area forced the pilots who at that time were operating over Texas to change from VFR-flight to IFR-flight.

Salt incrustation over the Mediterranean Sea, with its high chloride concentration, very often occurs in low level flight /19/.

For the sake of completeness, but also because of its increasing importance for the HSLLF the visibility reductions caused by the influence of the biosphere are still to be mentioned. Here first of all the insect-strikes at the cockpit-windows are treated whose varying frequency in dependence of different weather situations have never been systematically analyzed.

This work would of course require a continous and thorough analysis of all insect-remains on the aircraft and the correlation with the geophysical data such as temperature, humidity, and wind speed in the respective FL as well as in the entire friction layer.

The author's opinion is that this expense would be worthwile for 2 different reasons:

First, the insect swarms increasingly encountered in the LLF during the warm season are able to cause - according to the available incident reports - visibility reductions for the pilot from about 8 km down to less than 100 m. The crust layers on the windshields reached a thickness of about 4 mm; the author himself had to study a flight accident that could be attributed to a visibility reduction from 10 km to only 20 m because of insect strike in the LLF Fig. 14 and 15.

Secondly, an increase in the insect population, which can be regarded as a food supply for numerous bird species, show a strong correlation with bird massing. For this reason the "Air Force Engineering and Services Center Bird-Aircraft Strike Hazard Team" (BASH) began research on insect-populations /20/. It is to be expected that the extension of this work covering only a limited period of time (30.09.1978 - 12.10.1978 and 28.01. - 30.01.1979) will help to clarify the biological problems.

However, it should be emphasized that especially aircraft in the HSLLF evidently can be endangered exclusively by insect strike without regard to the visibility obstruction.

For example pitot tubes have been completely clogged by insects in LLF. During a flight over Sardinia the front windshield of the infrared sight burst after a grasshopper strike.

In order to clarify the population problem and its relationship to different weather types and flight levels the voluminous research material of the English research station Rothamsted should be used which has been given wide attention in the world's entomology and phytopathology /21/. Regarding the questions that have to be answered here reference is made to the fact that 42 flying periods of nearly 500 insect species were correlated with different meteorological data at this institute. The results obtained were later supplemented by the Research Laboratory for Advanced Entomology of the Technische Hochschule in Munich.

No further explanation is required for the general conclusion that, as has already been indicated, an increased bird-strike risk coincides with enlarged insect occurrences. Naturally - because of the more favourable vegetable food supply during the warm season - the frequency of birdstrikes generally rises at this time, Fig. 16. This is especially valid for the LLF up to 500 ft above the ground. In the FL above 1 500 ft, distinct maxima of birdstrikes due to the migrations in spring, and autumn occur in March and October. This is also indicated in the 500 ft graph, because obviously under certain weather situations some bird species use the LL. Hereby intermediate landing and take-off surely play a role.

Naturally, birdstrike cannot only produce a considerable visibility obstruction to the pilot but can also damage important parts of the aircraft, for instance, the engine. According to the graphs that have been shown here it can be expected that with a more frequent use of very low FL an increased number of birdstrikes should occur.

Concerning the adverse influence of the biosphere on the visibility it should finally be mentioned that at some given times less known phenomena can also contribute to dust concentration. According to Winkler this is for example valid for essential oils of specified plants forming aerosols and therefore becoming optically effective /22/.

The above mentioned author could not find any concentration of these substances below the inversion. This can be explained by the fact that essential oils do not escape into the atmosphere until the temperature is above 20° C. In most cases, however, the surface inversion has already been dissipated before reaching this temperature.

2.3 Wind

It has already been pointed out that turbulence takes the first place in listing the causes of flight accidents of the civil aviation of Austria. One possible reason for this peak might be the inclusion of the glider plane and light aircraft accident rate. Following the author's experience helicopters are also strongly subject to wind hazards, particularly in the autorotational flight phase.

Heavy turbulence can cause critical flight situations even for high-performance aircraft. This for example occurs in tropopause jet streams due to clear air turbulence.

Fig. 17 clearly demonstrates the frequent occurrence of turbulence in these levels, however the low level of the friction layer also experiences significant turbulence which has been verified by numerous test data for instance at the Dallas Tower in Texas and the Meppen Tower in Germany /23, 24/.

Increased low level turbulence has its origin in the frictional effects of the earth's surface which grow with relief energy.

Surface effects of the earth generally result in major variations of wind speed and direction. In Germany S. Uhlig was the first to draw attention to strong orographic influence in Alpine areas /25/. According to his investigations at wind speeds of < 10 kt in the free atmosphere directional variations of wind close to the surface of the earth of up to 160° clockwise and 180° counterclockwise have been observed over Altenstadt in upper Bavaria in comparison with wind data of the Zugspitze. There are still variations of 120° to 130° at wind speeds of > 10 kt. By a comparative study of wind data from Altenstadt and Kaufbeuren these findings were later on confirmed by other authors /26/.

S. Uhlig at the same time was the first to make quantitative statements on the low level jet (LLJ) of the Alpine foreland by theodolite observations of upper winds, Fig. 18. The LLJ, in fact, occurs with maximum frequency at altitudes between 200 and 400 m above ground.

Higher altitude of the LLJ which were detected later by the evaluation of the Munich radiosonde ascents (500 - 2 000 m) do probably not reflect the fair weather bias due to visual soundings. It is more probable that the LLJ like the tropopause jet may split finger-shaped in the vertical and horizontal planes, causing either the lower or the upper portion to act as the stronger LLJ. This concept would be in agreement with the fact that LLJ practically invariably is observed together with surface inversions which quite often are of multiple stratification. Incidentally, Sládkovic and Kanter have meanwhile furnished proof of the vertical LLJ splitting in the Alpine region, Fig. 19, /27/.

Without considering pending controversies on the origin and structure of the LLJ in detail, which can only be solved by an increased number of detailed vertical soundings, it must be emphasized in the context of the low level hazards under discussion here that the LLJ is a great safety risk also to high-performance aircraft, especially when under certain circumstances the "stall speed" in approaching a target is reached. The LLJ has a frequency of occurence of 33 % in all seasons in the Munich area and of 30 % in the North German lowlands. Wind maxima measured were 54 and 43 m/sec respectively /28, 29/.

In discussing low level flight it is important to know that shear winds of more than 1 m/sec/100 m most frequently are observed in the bottom layers. Maximum shear winds amounted to 17 m/sec/100 m thus exceeding the critical limits for aircraft.

Turbulence near the ground is further increased by the above-mentioned directional changes of winds in the horizontal and vertical. The variations are most striking when in a shallow surface layer of cold air the wind direction differs by 180° from that in the overrunning warm air mass.

Temperature lapse rates can reach very high values. The sudden reduction of air density which they bring about causes marked engine power drops so that in combination with turbulence the aircraft may touch the ground and crash.

It seems worth mentioning that several years' radiosonde data in the Munich area revealed temperature inversions of 10 degrees to have a frequency of 14 % of all days in January. Weber states a maximum value of 15 degrees for the 00-hour observations /30/. One can almost be certain to assume that at sun-rise, after reaching the minimum of the day, essentially higher temperature gradients will occur.

With foehn winds that do not sweep down to the ground even stronger inversions can be expected. These conditions primarily build up in basins where extremely cold air accumulates during the night.

One of the most famous examples of extreme vertical temperature gradients is the well-known Alpine pasture Gstettneralm near Lunz/Austria, where temperature gradients of more than 30 degrees per 100 m difference in height have been measured. In nights with strong radiational cooling cold air from all sides flows down into the dolina which is located some 1700 m above MSL so that primarily in winter time a regular cold air pool may form with temperatures as low as minus 50° C and less near the ground. Such extreme temperature gradients normally occur in arctic regions only.

Naturally, such a dolina of limited horizontal dimension can be a hazard only for aircraft submerging into the cold air during terrain following. It would constitute no special problem for helicopters. In any case a pilot must, however, expect considerable reduction of engine and rotor performance because of the fast change in air density when flying out of the dolina.

Similar conditions, though not as extreme, do occur in other internal drainage depressions. The author has knowledge of one case where during the night a cold air pool had formed in the crater of the extinct volcano "Plaidter Hummerich" near Mendig, Germany, which was used by a VERTOL aircraft for take-off and landing practice. During this training a serious flight accident occured which was caused by the aircraft taking off from the cold air mass of the crater and hovering in lowest level flight into one of the open pit mines directly on the edge of the crater where in the absence of any protective vegetation the volcanic rock had been heated up to +60° C by unhindered insolation. On reaching the edge of the crater a sudden engine power drop caused the VERTOL to hit the ground and crashed into the pit, Fig. 20, 21, /31/.

High-speed aircraft are, as a matter of fact, not subject to hazards of such small-scale cold air pools. Depending on the size of the pit also high-speed fixed wing aircraft may encounter a similar situation. There is at least one known case where a pilot dared to fly in low level into a large open pit brown coal mine, Fig. 22. Here high air temperatures caused by the high insolation and low heat-conduction of the brown coal reduced the density of the air considerably. This brought about marked reduction of engine power which nearly led to an accident. Similar cases may occur near extinct volcanoes especially when the low heat-conductivity of the volcanic material is further reduced by a superimposed layer of extremely porous diatomites, Fig. 23, which consists mainly of fossile algae detritus.

Problems could also arise in internal drainage depressions for instance in wide Karst basins (Polje) that may at least cover several hundred km². If in those areas the top of the inversion is located close to the edge of the basin the aircraft may crash due to an abrupt engine power reduction when emerging from the cold air layer. This hazard is enhanced in the case of coincidence of temperature inversion and a moisture inversion and turbulence.

There is considerable turbulence in windward and lee eddies near mountain crests. In the case of high winds these gusty areas are not always manifested by rotor cloud formation so that they may become a serious threat to aircraft in low level flight.

R.A. Cashmore reported on the heavy turbulence affecting low level flight over the United Kingdom /32/. For jet aircraft, the type of which was not specified, he stated acceleration forces from -0.75 to +2.1 g.

W. Georgii has reported acceleration forces of 3 to 6 g for airliners in rotors of leeward eddies /33, 34/. In general vertical speeds within rotors are extremely variable. In high reaching eddies for example at the Großglockner drafts of 15 m/sec occured. Even higher values are likely to occur in the Owens Valley leeside of the Sierra Nevada mountains, which are 4 000 m in height.

A typical aspect of those high reaching eddies is the fact that the turbulence is enhanced close to the ground due to the supply of the thermal energy. Rotors are further increased by the resonance of lee waves due to the configuration of the terrain. If for instance parallel mountain ranges, are spaced in an optimal way, lee waves which are in phase and their rotors may increase considerably in the case of specific wind directions. In Germany this happens for instance with SW and NE air flow in the hill areas of the Weserbergland, Süntel and Deister causing lee waves of 14 km in length. Fig. 24.

Owing to the tectonics of the geologic foundations, which in no way are random, similar phenomena are common. Samples are the Palatinate Forest, Taunus mts, Vosges, Black Forest, Swabian Alps /35/. Recent analysis of satellite cloud photographs has given proof of that view.

In the case of a strong inversion above the mountain ranges a jet forms between the surface of the mountain range and the top of the inversion which may lead to critical speeds in the eddies. This is particularly true when as pointed out earlier additional thermal energy from the surface contributes to enhancing the turbulence. Condensation processes naturally act in the same way. They even aggravate hazards due to turbulences by adding visibility problems.

This for instance is the case when stratiform cloud formation takes place below thunder clouds. In arid zones engine trouble may occur according to pilot reports when at the same time dust is whirled up due to convectional turbulence. In low level flight it is not uncommon that bending limits of the aircraft GCA antenna are exceeded by heavy wind so that heading and altitude information from the GCA become inaccurate and perilous /36/.

There is no need to discuss here in extenso the warm and cold fall winds because they are generally known. Mention should, however, be made that Bora wind speeds of up to 50 m/sec have been observed. Every pilot who has flown in the valley of the Rhône river is familiar with the adverse effects the Mistral wind can exert specifically on low flying aircraft. Katabatic winds of limited extent may of course also have an influence on light aircraft. They occur in various areas having local names for example Weißenburger Wind, Höllentäler, Wisperwind, Bohemian Wind etc.

During the warm season of the year low level flight is mainly affected by convectional turbulence. Gusts are most violent within the up- and downdrafts of thunderstorm cells. Together with abrupt changes of head-, tail-, and crosswinds they might cause critical flight situations in high speed low level flight of aircraft.

2.4 Thunderstorms

Problems of visibility, wind, and erosion in connection with thunderstorms have already been discussed in the foregoing chapters.

During low level flight in thundery weather, the aircraft enhances the field strength between the earth's surface and the thunder cloud so that in this area of a raised potential gradient a high discharge rate is encountered. The hazard becomes even worse when the cross section of the conductor is enlarged by other aircraft flying in echelons formation. Ionized hot engine exhaust gases incidentally act in much the same way so that, a priori, multiple jet engine high performance aircraft are more exposed to lightning hazards than aircraft with less fuel consumption /37/.

Vertical speeds in thunderstorm cells are generally faster in mountainous terrain thus enhancing the electric charges in the clouds. The number of lightning strokes is increased and the frequency of cloud-to-ground lightning is much higher than that of cloud-to-cloud lightning thus the risk of lightning-stroke is raised noticeably over mountain slopes and crests; potential lightning risk over southern Germany is twice as high as over her northern part /38/.

It has already been mentioned that the raise in the electric field strength by the aircraft is also dependent on its engine performance. Furthermore the structure plays a significant role. The different position of the pitot tube on several models of the Phantom F4 aircraft plays an important role with regard to the lightning stroke rate as shown in the table below /37/:

type	pitot tube installed in	lightning stroke rate per 100 000 flight hours
F-4D	tail section	0.89
F-4C		1.76
RF-4C	nose	3.11
F-4E		3.40

Navigational and control instruments may not remain safe after lightning strokes.

Crew members are frequently subject to adverse physical and psychological effects by electrization, blinding, and shock so that delayed or improper pilot reaction may lead to crash-down.

2.5 Sleet and Hailstones

Some light has already been shed on the damaging effect of raindrops to high-speed aircraft. Of even higher importance in nature are sleet and hailstones acting like the impact of bullets on the aircraft. Considering that the shelltype structure of hailstones is proof for the repeated ascent and descent of the ice pellets within the turbulent regions of the thunderstorm cell it must be concluded that generally hailstones reach their maximum weight by accretion and the freezing of cloud droplets during the last phase. This is fundamentally valid when in downdrafts the freezing level is low, thus precluding the melting process.

The melting of hailstones is not even effective in summer, Fig. 25. This view is supported by the relatively frequent hail falls in southern latitudes where predominantly higher elevations are affected. Example: On January 15, 1980 a simple hail storm damaged 33 % of the carrier fleet of the "South African Airways" in Johannesburg, 1694 m +NN: 4 Boeing 747, 4 Boeing 737, 1 Boeing 727, 2 Boeing 707, 1 Airbus.

2.6 Medico-meteorological Problems (med-met-problems)

The foregoing chapters have demonstrated that geophysical hazards are at their maximum in low levels. It follows that an extreme reaction ability of the man-machine-system in that domaine is an absolute requirement.

The question arises, whether the pilot's reaction time may not likewise be influenced by certain geophysical factors.

During World War II, B. Düll was the first to look into this problem thoroughly in Germany /39/. It may be worthwhile to recall some of Düll's most essential findings and compare them with recent studies under the aspects of High Speed Low Level Flight problems to be discussed at the Lisbon meeting. In doing so a reasonable degree of criticism is necessary because one can never preclude errors in the borderland between medical and meteorological sciences. The author as a geophysicist has chosen to restrict himself exclusively to a discussion of the geophysical aspects of the problem.

Because results of reaction time measurements vary considerably with the type of experimental arrangement, as is generally acknowledged, it is only reasonable to compare solely results derived by one and the same test method.

Düll's experimental setup had been designed to determine the "net" reaction time, because the immediate objective was to find out if there are variations in reaction time in responding to a certain stimulus man is confronted with. "Net" reaction time is defined as the sum of the following periods of time:

- perception of an optical or acoustic signal
- response in terms of the smallest motor movement:
  pressure exerted by the index finger which already touches the key.

This then is only a determination of time elapsed for:

- transmitting the stimulus from the eye or the ear to the central nervous system, and
- transmitting the order from the central nervous system to the motor organ, i.e. the index finger.

It would, however, not be acceptable if one would draw conclusions from the human "net" reaction time on the reaction time of the man-machine system. On the other hand it is thought possible and even likely that similar to the generally accepted fact of a pilot's quicker reaction time in anti-cyclonic weather situations, the aircraft itself may react by a decrease in performance when penetrating a pronounced inversion layer. The reaction time of the total man-machine system is then balanced out. This problem will be refered to later. In other cases geophysical factors may also produce reaction times where both components of the system have the same direction so that a critical flight situation may occur due to an additive prolongation of the reaction time.

As for the synopsis of the man-machine system being within the scope of the article, it is a fundamental requirement to consider the accumulation of all forces.

R. Reiter's investigations into the man-automobile-system inferred that it may be admissible to assume the changes of reaction time of both components being in the same direction. This simplification however, is not allowed in aviation.

It must be underlined that speed and correctness of the reaction are not necessarily in conformity with each other. Finally, the question has remained unanswered whether the simple process of responding to a stimulus by pressing down a finger is comparable to the affect of the variety of signals working upon the pilot and their conversion into commands and orders that in turn must be followed by complex motoric cycles of various muscle systems.

Recent studies of the Fraunhofer-Gesellschaft in Munich have revealed that reaction times in the cockpit of any means of transportation are longer than the "net" reaction time given by Düll /40/. Düll's finding that the reaction time is noticeably shorter following an acoustic rather than optical stimulus was verified. On the average, braking or slowing-down is carried out after 0.6 seconds on optical signals whereas only 0.2 seconds pass after an acoustic signal. Individual cases were noted where delays in reaction time up to 3 seconds were measured when optical signals had been employed.

On the basis of these facts the Fraunhofer-Gesellschaft rightly recommends that electronics used in the automative industry be modified to give primarily acoustic information to the driver. There is no doubt that such experience must also be applied to aircraft construction.

Consequently, General Schmitz, who is responsible for the flight safety of the German armed forces, has emphasized this military requirement to aircraft designers during the 12th Helicopter Forum held at Bückeburg from the 8th through the 10th May 1978 /41/.

A cooperation between aircraft constructors and flight surgeons seems to be necessary, to avoid constructions like the "Airbus Master Caution Unit" which produces a multitude of signals at varying tone levels, causing pilots to ironically call it "The Airbus Symphony".

The difficulty of research work for most efficient layout of display and controls is shown by the recently published "Analysis of Heart Rate Variability as an Estimate of Pilot Workload in Human Engineering Research" (DFVLR, F.R. Germany, Sept 1979). The "Method for Semi-Automatic Analysis of Eye Movements" as applied by the "Institut für Flugführung" of the "DFVLR" seems to be a very important tool for human factors research on the layout of displays and controls /42/. By means of such research the problem of the best strategy for identifying a target by eye sight may also be solved /43/.

The problem of "net" reaction time and its dependence on geophysical parameters is dealt with in the following section:

During half a year (July - December) R. Düll tested the reaction time of one male and one female individual, daily 5 times each at 0700, 1300, and 1900 hours on an optical and acoustic signal (i.e. 30 test runs per day). The following results were obtained, Fig. 26.

a) Basically, the curves for both individuals are in conformity.

b) The mean reaction time of the male person is shorter by 5.4 milliseconds.

Whether these individual data can be generalized is of course debatable, although Düll makes reference to the verification of his data derived from test series of 25 US male and female university students.

c) The reaction time upon acoustic stimulus is noticeably shorter than to light stimulus (25 milliseconds).

d) The reaction time measured at 1300 hours is slightly shorter than that at 0700 and 1900 hours.

e) The reaction time in the fall is distinctly less than in summer and winter.

Düll assumes "with all reservations" a bimodal seasonal distribution of reaction time with extreme values occurring at the solstices and equinoxes. His reservation, obviously based on reduced periods of observation was justified as shown by later investigations carried out by Daubert /44/.

The analysis of ten-year observations made at Tübingen resulted in a single seasonal oscillation of reaction times with maximum values in March and minimum values in September, Fig. 27.

This unexpected curve of maxima and minima at the equinoxes, i.e. at times of similar solar radiational conditions, proves that there exists no simple correlation between reaction times and astronomical processes. Rather, there seems to be a relationship between reaction speed and meteorological meso- and microscale phenomena obviously compensating the radiational effect.

However, it has not yet been fully clarified to date what meteorological parameter or combination of various parameters are the controlling factor of reaction time.

With good reason Daubert states that "never only <u>one</u> element influences the human organism, but always <u>all</u> stimulant factors of the atmosphere complement, sum-up or weaken each other in their combinatory play".

Taking also into account that the biological reaction in most cases is delayed due to the necessary accumulation of varying stimuli, it is realized what a complex job it is to clearly define the causal relations between reaction time and environmental factors to which those of the private sphere must be added, too.

Neither does the determination of very high correlation coefficients tell anything about causality, because the correlated parameters may be interdependent.

The close correlation between the reaction time and the intensity of atmospherics (atmospheric-electrical parasites in French) found by R. Reiter, does not prove any causality between the physical and the biological processes /45/. Spherics are closely correlated to instability zones (cold fronts, troughs) so that it is justified to assume that reaction times are dependent upon temperature, humidity and wind speeds as well. It is generally known that the latter factors determine the degree of sultriness and this in turn determines the feeling of comfort, which the reaction time depends upon.

This is, as Reiter justly states, the explanation for the test results of reaction time obtained from some 40 000 individuals on the occasion of the Munich Exhibition of Traffic and Transportation in 1953:

It was found that heat and sultriness during the period of August 26th to September 3rd were the predominating influences which overcompensated effects of spherics on the human reaction time. Fig. 28.

Any attempt to analyze a complex biological process as a function of only <u>one</u> single meteorological factor, must a priori be deemed mere speculation. This is especially valid when the comparison is based upon averaged data calculated from very different extremes.

Therefore, it is not admissible to generalize the statement made by Düll that on the average the days characterized by improved reaction times showed higher air temperatures than the days of slower reaction times.

Uncritical comparison of reaction time data with meteorological data may result in controversial statements such as the one made by Düll that improved reaction times are correlated with low visibility!

He found the mean reaction time to be lowest in continental tropical air where it amounted to 161,6 milliseconds. According to Linke's turbidity factors, which are an intrinsic property of the air mass, however, visibility in this air mass is so reduced because of the high aerosol content. Thus the controversal statement is made that low visibility is correlated with good reaction times. For ophthalmological reasons this conclusion can only be drawn with test persons whose reaction times are measured within a laboratory using a light signal on shortest distance so that the obscuration of the ambient continental tropical air has not the slightest effect on the reduction of the optical stimulus.

It can be taken for granted that a test of reaction times by the application of an optical signal from a farther distance in the free atmosphere would turn out to be quite different. Therefore there is no doubt that the pilot's reaction capability is, reduced in the turbid and normally hot or sultry tropical air.

This example quite impressively demonstrates that data derived from laboratory tests must be applied to the realistic conditions of the ambient environment with great caution.

Similar critical consideration should be given to Düll's investigations of the reaction time as a function of the sunshine duration.

What matters here - as most everywhere in the field of medicine and biology - is the dose and time of administration. If the sun is in the pilot's back and at an angular elevation forming optical contrasts in the terrain by shadows his reaction time will no doubt be influenced favourably. This, however, applies only as long as no excessive amount of insolation heats the cockpit.

Based on these explanations it is in no way strange that Düll "was unable to discern a firm relationship between reaction time and duration of sunshine".

A similar comment can be given to Düll's statement on the absence of any relationship between reaction time and precipitation. The correlation with precipitation might originate from the noise accompanying for instance hail and thunder storm that could divert the test person's attention. Düll's hint that thunderstorms reduce the reaction time is in support of this view. A significant factor in the cockpit of course is the dazzling effect a lightning flash has on the pilot's eyes resulting in a reduction of observability.

Noteworthy is Düll's statement of the very close correlation between the stormy days of the German coastal area (wind speed > 8 Beaufort) and the prolongation of reaction time measured in Hamburg.

It is probable that there is an enhancing effect by microseismics which according to H. Berg are caused by the ocean surf; these microwaves have periods of 4-to-10 seconds. They are felt inland at varying distances depending on the geological terrain features. /46/

Perhaps microseismics have similar adverse biological effects upon man as do rometric oscillations, which according to E. Brezina and W. Schmidt reduce the working capacity or according to Düll the reaction time /47/. The latter quotes periods of between 6 and 12 seconds for very fas barometric oscillations which is similar to H. Berg's values for the microseismics, so that a causal relationship between litho- and atmospheric oscillations is inferred.

Physicians, however, are challenged to answer the question, whether Storm von Leuwen's view on the physiological effects of infra sound waves in the "flutter range" are correct /48, 49/. This "flutter range" is also characteristic for certain fluctuations of the earth's magnetic and electric field. A biological effect possibly exists inasmuch as the electric action centers of the human brain also have their greatest amplitudes in the "flutter range".

In view of the a.m. complexity of the performance it should be emphasized, however, that the predominating control of single factors as for instance barometric oscillations can, if at all, be confirmed only for very specific activities.

With that in mind it is worthwhile mentioning that H. Reuter in a recent study restricts the validity of his statement on the temperature - dependent efficiency to only a few categories of workers, for instance sheet metal workers /50/. Just as is the case with different types of sports, the optimum performance is achieved in individual occupational activities, when a specific comfort temperature is provided, which in turn is related to a specific relative humidity and wind speed.

The generalisation of medico-meteorological correlations obtained in a confined area of activity as being typical for other areas is not acceptable .

Thus it can be taken for granted that the dependence of the reaction time on seismics and barometric oscillations is completely insignificant for the pilot in flight. Even if lithospheric vibrations would affect the aircraft and its crew while on the ground the conclusion can be drawn beyond any doubt that, at the latest, after the start of the engine inherent vibrations

overcompensate by far this influence on the man-machine system.

From the geophysical standpoint consideration is also given to the fact that seismics in industrialized countries are not only due to oceanic surf, but primarily due to traffic and transportation and other man made vibrations of the ground.

For reproducible evidence of the effectiveness of individual factors on the human reaction time a simulator would be required to determine the response to one specific element by eliminating all other ones. The construction of such a "geophysical chamber" would, however, lead to considerable financial expenditure.

Such an installation, however, might be justifiable for the solution of flight medical problems concerning the effect of various geophysical factors. In any case it would help to avoid the "biased" approach and insistence on certain medico-meteorological relations that Düll criticizes. In the overwhelming number of cases certain biological effects are likely to be brought about only by the synergism of miscellaneous geophysical factors.

Medico-meteorological research therefore has meanwhile abandoned the study of single factors like aran, spherics, infra sound waves, and is making attempts to clarify the interplay ("accord") of various single parameters.

Though measuring the reaction time is a difficult physical task, Reiter was able to find that the reaction time might be reduced from 253.2 milliseconds to 181.0 milliseconds by training. The fact that training plays a significant role, indeed, and varies individually, is an indicative that the reaction times obtained ought to be interpreted with caution. According to what Russian flight physicians have determined, the reaction times of experienced pilots are generally believed to be faster by a factor of 1.5 to 2 than those of junior inexperienced pilots /51/.

As mentioned earlier the point in question still is whether the speed of reaction is equivalent to the soundness of reaction. Only when both are identical a correlation between spherics and accident frequency ought to be found from R. Reiter's observational data. H. Lossagk states that 50 % of all traffic accidents happen because of the driver's impaired ability to react /52/.

When processing statistical accident data the analyst, however, enters a domaine that may easily render him a victim of the pitfalls and mantraps of statistics.

So for instance the statistical n-method, when picking the afternoon as the period under investigation, will inevitably result in a coincidence of higher accident tolls (increased traffic volume in the afternoons) and higher frequency of spherics. As a rule, spherics also occur mor frequently during the second half of the day because of intensified instability of the air near the ground.

Comparative tests on accident frequencies prior to and after the introduction of flexible working hours would for sure prove that the correlation with the spherics now is by far not as close as before. The choice of proper statistical methods with equidistant time intervals may help to correct biased results.

For the spherics it should be remembered that they primarily occur in cyclonic processes, mainly in connection with cold fronts and throughs, in other words, in rain and snow showers, partly in thunderstorms. Often the sudden onset of these weather phenomena brings severe hazards such as aquaplaning or slippery road conditions. Additionally, these reductions of trafficability can be enhanced by other characteristic features of cold fronts and throughs as gusts and visibility reduction thus raising the risk of an accident.

Noth et al. therefore seem to be right in expressing their doubt whether the frequency of accidents is based purely on "biotropical" weather effects /53/.

The synchronous occurrence of accident data and spherics in "the absence of meteorological incidents of a specific type", for example precipitation and thunderstorms, is no counter-evidence. Recent observations have revealed that the intensity of precipitation is liable to considerable fluctuations during cold front passages due to topographical conditions. The same holds true for visibility, wind, and - especially in higher levels - the cloud base. From this it follows that a statistical analysis of the accident rate claiming to be of scientific significance must aim at the careful study of each individual case. Under no circumstances meteorological data of the nearest weather station should be allowed for extrapolation without caution, because that station might for instance be located on the leeside of an orographic obstruction; thus its good weather conditions might not be valid for the site of the accident which might be located in an extremely windward position with markedly unfavourable weather conditions.

In this context it should be emphasized that also in lowlands the local fluctuations in the effects of cold fronts and throughs can be relevant. Therefore, in spite of comprehensive data from 68 000 traffic accidents in Hamburg, analyzed by Köhn, no proof could be furnished so far of the influence of spherics /54/. This is also supported by Schröder's measurements of very long waves in Hamburg which did not show any coincidence with accidents /55/.

Because of these discrepancies it is justified that Israel, one of the best authorities on atmospheric electricity, considers the causal relationship between accidents and spherics as a physical freak like a divining rod and earth rays /56/.

Apart from Israel, distinguished physicians and physicists like Abele, Prokop, Kühnke, Zoller, et al. have pleaded against the one-sidedness of the advocates of specific philosophies in their books "Wünschelrute, Erdstrahlen und Wissenschaft"(divining rod, earth rays, and science) and "Medizinischer Okkultismus" (medical occultism) /57/.

To prove the effects of spherics on accidents it is not admissible to point to the different percentages of the increase of the accident toll due to slippery roads in cases without (6.5 %) and with cyclogenesis (40 %). Obviously the number of accidents must not be seen as a function of the frequency of slippery road conditions but as a function of its absolute duration in relation to the traffic volume. Besides it can be anticipated that the accident risk with cyclogenetic processes is enhanced by reduced visibility and the influence of wind.

The effectiveness of spherics is not evidenced either by the evaluation of industrial accidents because the results are often biased: Statistics do not tell whether for instance slippery conditions have caused the accident or not. In this respect the preclusion of accident statistics of specific trades like building or shipping does not improve the basic material as long as it still contains the data of those trades that are practically always exposed to the weather like agriculture, quarries, opencast mining, etc.

This information is indicative of the fact that in order to obtain an unbiased result it is absolutely necessary to filter out all those cases from accident statistics that according to meteorological data were beyond all doubt caused by trivial weather factors. It is better to work with a smaller but purified collectiv than to deal with a non-verified mass of data.

A separate analysis of the data of underground mining again must be carried out with caution because these areas "are shut-off from natural weather rather completely".

After the war there has been quite a number of underground mining installations which are subject to surface water seeping in very fast through cracks of high permeability. In addition the trucks continuously returning from the open air in rain or snow introduce the potential risk of hazards of a meteorological nature into the underground mining facilities. This hazard is not to be overstressed here. It is, however, certainly worse than that of possibly increased spherics at the time of the beginning of the shift under the influence of which the mining worker is supposed to bring down into the pit "strongly increased preparedness for accident". The latter statement may or may not be termed a speculation. But there is no doubt that the conclusions in the domaine of industrial medicine drawn by those supporters of the spherics theory are highly objectionable. They for instance hold the argument that "improving ventilation and air conditioning are not considered necessary" because of the hypothetical importance attached to spherics triggering an accident.

Transferring these ideas to the air conditioning of the cockpit would be irresponsible with regard to flight safety.

Meanwhile profit-seeking manufacturers of air conditioning devices take advantage of the above statements in taking up the production of "pulse field devices". These devices are meant to produce "favourable" electrical fields in working and living areas, but also in automobiles, and recently, even in aircraft /58/.

Since no proof could be furnished so far for the causal influence of natural atmospheric electrical fields, some doubt must be expressed as to the enhancing effects of man-made atmospheric electrical fields on human reaction capability.

It must be highly appreciated therefore that Reiter takes a clear stand against the speculators of "pulse field devices" in a new publication /59/. His arguments like: "For the effectiveness of atmospheric electrical parameters there is no receptor in the organism that can directly respond and signal the stimulus" and also "i should be considered that temperature, relative humidity, air movement, heat radiation, etc determin the cryptoclimate" reveal that Reiter is now looking at things in a more sophisticated way than he did before.

As far as spherics are concerned the above author states that "they are only of second order in their influence and can be overcompensated any time by other environmental factors".

The fact is stressed that man himself creates a significant level of electrical interference overcompensating all standard fields by use of clothing, synthetic materials, electrical equipment etc.

With regard to the incorporation of atmospheric ions Reiter says that "strictly speaking no biological effect is to be anticipated". "Ions, however, are adsorbed by the ever present aerosol particles which due to their low mobility have a good chance to reach the respiratory tract and eventually trigger biological effects."

Medical scientists (Ranscht-Froemsdorff) state that "the effects of natural and man-made spherics are diminished or become ineffective by modified environmental conditions as for instance temperature, room lightning, atmospheric pressure. A growth in human preparedness to reaction and mental performance could not be established by any one program" /60/.

By this statement the author mentioned above gives up the statement he made in 1974 that in "specific electro-climate chambers serial testing of volunteering student groups during a permanent stay inside inferred direct biological effects of spherics on the functional and biochemical parameters of blood coagulation, blood count, blood sedimentation rate, blood pressure, pulse rate, temperature, reaction time, allergic vulnerability, mood, and sleep behavior" /61/.

In 1975 the medical relevance of the electro-climate was turned down by Jessel, Wedler, Kröhling and others during the 80th Congress of the "Deutsche Gesellschaft für Physikalische Chemie und Rehabilitation " at Freiburg/Breisgau. Summarizing the outcome of this congress Göpfert states that "no conclusions can be drawn from this for practical use" /62/.

Within the geophysical community there is no doubt regarding the biological ineffectiveness of commercial pulse field devices on the market now.

In 1976 and 1977 several authors tried again to convince people that the influence of atmospheric electrical fields should be an objective of accident research. Thus, the "Bundesanstalt für Straßenwesen" in Germany together with the "Deutscher Wetterdienst" and the "Bundesministerium für Verkehr" were challenged in 1978 to issue a critical review on pros and cons of that complex. The "Bundesanstalt" was fair enough to offer a meeting where proponents and opponents were given the chance to frankly discuss their respective opinions.

The expert hearing at the "Bundesanstalt für Straßenwesen" in Cologne resulted in plain refusal /63/: No side was in contradiction to the argument that

> "results of tests under review did not give reason to recommend installation of field generators in automobiles".

On the contrary, prohibitive action on this equipment was considered because "the motorist, possibly depending on the effectiveness of the generator, may be misled to the believe that he may perform better than usual".

For formal legal reasons, however, it is not possible in Germany to take any prohibitive action against the construction and distribution of field generators.

There is no doubt the fact that the installation of such equipment in aircraft must from the beginning be precluded for flight safety reasons, especially in the military aircraft.

This is strongly supported by information received from institutes outside Germany, for instance from the "Naval Aerospace Medical Laboratory, Naval Air Station, Florida", where unbiased animal test series furnished no evidence of any relationship between the reaction time and electromagnetic fields in any kHz frequency range, not even after test series of more than 1 000 hours duration /64/.

"Day-to-day variations" are "much greater than field-to-field variations" was the noteworthy comment.

Another interesting finding is that none of 23 different blood tests (creatine, hemoglobine, potassium, etc.) revealed any dependence on the extremely low frequency field (ELF-field).

This verifies the results obtained by D.E. Beischer, J.D. Grisset et al. in 1973: "No differences in reaction time in either man or monkey were produced by the ELF-fields" /65/.

In one of their recent works on the weather influence on accidents Jendritzky, Stahl and Cordes have made an attempt at an objective assessment of the effectiveness of the individual weather factors /66/. However, these authors did not make critical selections of their accident data either. Likewise, they did without a detailed analysis of the orographic conditions at the location of the accident to determine a possible variation of the local weather from that of the nearest observation station. Thus, as mentioned before, no precise statement on the effects of environmental stress, as for instance subtropical air, could be made.

Moreover, the test area of Saarbrücken chosen by the a.m. authors is definitely unsuitable for the investigation of the natural weather influence on accidents because of its intensive industrial and urban emissions. The "Arbeitsmedizinisches Zentrum" of Saarbrücken has emphasized that air pollution strongly affects the health condition /67/. Taking into account that the air pollution even influences the mortality of man it must be concluded that the reaction capability is affected, too.

This assumption is supported by the fact that the percentage deviations in the accident rates in Saarbruecken are highest in anticyclonic weather situations with southwesterly to northwesterly flow. Industrial plants are located in the directions mentioned having a high output of sulfur dioxide (SO_2), as for instance the Völklingen-Burbach and Forbach ironworks.

In the presence of such measurable emissions, which are a heavy load on the human health, it is unnecessary to search for a hidden agent being the cause of accidents.

This statement in no way is intended to express any doubt about the environmental stress resulting in discomfort as for instance under Foehn conditions.

In the German military domaine it was G.E. Stolley who specifically stressed the biological significance of emmissions /68/.

Because of their extremely high concentration just beneath the top of the inversion pollutants may adversely affect the pilots' health when flying in low levels without an airborne oxygen supply. This especially holds true in wartime when the toxicity at this level may be raised by a factor of 100 to 1 000 by traces of biological and chemical warfare agents. Coalescent together with adsorptive processes and the absorption of water or water vapor in these cases results in the trapping of these pollutants over extended periods of time.

Furthermore, E.Plötzke referred to Goetz's enhancing effect in his discussion of the effectiveness of chemical warfare /69/. According to his statements it consists in an "extraordinarily remarkable pathophysiological effect of chemical warfare of smallest concentration caused by complex molecular kinetic processes acting on natural aerosols". Conversely, molecular shielding (Gibbs effect) can also produce a neutralization of chemical warfare.

These references are necessary with respect to the cooperation between physicians and geophysicists. In wartime, preventive measures are required to prevent flight accidents due to toxic effects. It could primarily be aimed at calculating - for instance on the basis of S. Uhlig's method - the stability index of the lower atmosphere which besides the wind decisively influences the propagation of pollutants. Another province of joint medical and geophysical effort is the definition of optimal air conditioning of cockpits.

Modern combat aircraft are subject to unhindered insolation through the clear vision canopy producing increased heat stress and sultriness.

This is especially true in tropical and subtropical regions. The Germans studied these problems in North Africa during the World War II /70/. During the AGARD-meeting of 1968 R. Goldmann gave detailed information on the thermal comfort in flight and its effect on performance /71/.

A recent paper describes the physical effects of the heat stress caused by the greenhouse effect of the F-16 fighter /72/. It reads: "There is no doubt that heat stress produces a significant decrease in reaction time together with a rise in error rate".

This finding is in agreement with the results obtained by M.F. Allnutt and J.R. Allan /73/.

The test data of all authors thus verify the adequacy of J.O. Lorge's and J.D. Grisset's concept that the reaction capability is not dependent on any electromagnetic fields, but rather on temperature, humidity, and barometric pressure.

The authors mentioned above are right in assuming some synergistic effect of the parameters listed.

It is a difficult job to clarify this synergism with the help of a medico-meteorological computation model.

Fanger's comfort equation used by the "Deutscher Wetterdienst" could offer a suitable approach. Not only does it provide for air temperature, air humidity, ventilation and radiation but also for activity and clothing of the test person /74/.

The application of this approach to the cockpit comfort, however, is difficult due to the microscale temperature variability in the aircraft.

Following the test data obtained by Sönning, Könen, and Knepple ultraviolet radiation should also be included in that concept /75/. They found that these rays affect "the heat balance of man insofar as they are significantly involved in hyperthermia". In addition, ultraviolet radiation directly affects the nervous system. The cumulative effect of the total radiation therefore must be viewed from different standpoints for various flight levels.

When considering the affect of UV radiation on the pilot the question of the absorption by the cockpit windows is obviously important. Vogt of the DVLR informed the author that the synthetic material used for cockpit windows in military aircraft shows unhindered penetration of UV rays.

Because of the individual differences in the affects of the cockpit climate only approximate comfort data for the "standard pilot" can be evaluated so that practically the air conditioning must be adjustable following the individual comfort equation.

The heat problem, at least in part, could possibly also be solved by medical-preventive measures. Investigations of the "Institut für Klimaphysiologie, Universität Freiburg i.Br." have disclosed that heat-adapted personnel are capable of increasing their physical performance /76/. This ability of compensating for high temperatures can be explained by cellular adaptation which is more effective than the adaptive enhancement of the ventilation of the lung.

As for the pilot's task in the cockpit, a medical comment would be required on the applicability of the findings of the above Freiburg institute, namely an increase of physical performance by 10 % of heat-adapted personnel measured with the help of an ergometer.

In this context the following private communication to the author by Prof. Dr. Dr. F.G. Sulman (Department of Pharmacology and Therapeutics, Bioclimatology Unit, Hadassah University, Medical Center Jerusalem, Israel) on the 14th September 1979 is also of interest. Test series with summer and winter adapted athletes revealed an increase in performance in the respective temperature ranges.

The geophysicist cannot comment on this problem. His prime task is to inform the pilot so that he uses the optimal flight level on the optimal flight route.

In doing so special attention must be given to the prefrontal processes (phase 3 and 4) which according to M. Kreipl undoubtedly contribute to pilots' errors and flight hazards, Fig. 29 /77/.

So far it is of minor concern whether in these cases the pilot's reaction is solely due to environmental stress or also due to trivial weather phenomena.

3. SOLUTION TO THE PROBLEM

It has been explained in the foregoing chapters that the atmospheric conditions in the lower friction layer are highly influenced by the lithosphere. This implies that those geophysical factors which affect low level flight can substantially differ from those observed at the airbases.

During the World War II the Germans gave met. support by describing the meteorological conditions along frequented flight routes. They were of course only capable of taking into account flight meteorological data relevant at the time when the weather reconnaissance flight was conducted. By repeating the flights in different weather situations, however, comprehensive data were collected for meteorological support to later flights on the same route.

Additional weather reporting stations were set up for all routes. They were mainly post office agencies and their personnel had been briefed on weather observation.

In this way relevant factors like visibility, cloud base, wind etc. could be requested by phone any time in marginal weather conditions.

Generally this system worked so well that it is still partly in use, to back up the met. support. In some areas guardrooms of barracks and other military installations serve as auxiliary weather reporting posts that can be called up around the clock.

This procedure is a more or less adequate means for the better interpolation of the data measured or observed by the technical personnel of the official weather stations.

It need not be pointed out that in future for high speed low level flight more precise information is required. After a false prognosis a modern jet aircraft can only make an emergency landing on undestroyed Autobahn strips when an air base is not within reach in wartime. Moreover, for the accomplishment of the military mission it is necessary not only to forecast the weather on the flight route but rather that of a larger flying zone so that the pilot may be able to choose alternate routes.

This means that the forecast would have to be converted from mere route to zonal weather support, including the recommendation to the pilot which route he should prefer for the fulfilment of the sortie.

The best tool for the selection of the optimal flight routes in low level, no doubt, is a digital terrain data base, supplemented by geophysical inputs.

The German Ministry of Defense therefore has procured a "topographic terrain data base" also suited for other purpose like for instance military technology.

In this system the territory of the Federal Republic is broken down into squares of 150 m in length in north-south and 95 m in length in east-west directions /78/.

Each field contains the following information:

- terrain elevation in meters
- topographic values:
  1. large residential area, major town, industrial area;
  2. small residential area, small city, village, settlement;
  3. coniferous forest;
  4. mixed forest;
  5. deciduous forest;
  6. heathland, shrubwood, dwarf pine wood;
  7. dry plowland, sand, gravel, rock debries;
  8. wet soil, moorland, swamp;
  9. fresh water;
  10. ocean.

In cooperation with the holder of the terrain data base (Industrieanlagen-Betriebsgesellschaft (IABG)), the "Amt für Wehrgeophysik" has supplemented the terrain data base by inputs of meteorological and plantphenological data for some areas /79/.

For efficiency reasons all squares that did not show any significant meteorological differences were combined into larger units with uniform weather features. Meynen's map of the "Naturräumliche Gliederung" (classification of natural regions) was used in that process /80/.

The problem now was to assign to the individual natural squares lacking weather observations regularly reporting weather stations nearby that - for reasons of topography and climatology - can be assumed to experience similar weather.

These corresponding areas are interchangeable depending on varying weather situations, seasons or time of day.

This type of inter- or extrapolation will provide for better met. support in each individual case. The data inputs of the working group on "Regional Flight Climatology" of the "Deutscher Wetterdienst" and "Amt für Wehrgeophysik" are also used. This group conducts analysis of all experience gained in civil and military aviation and evaluates all publications it can get hold of in the field of flight climatology /81/.

A complete data base should contain additional data relevant for flight information, for instance phenological data for problems of camouflage, ornithological information for birdstrike hazards, pedological details for dust formation and visibility reduction, oceanographic data on wave heights, glazy sea and saline displacement. Thus the terrain data base must be supplemented in the framework of a technical information system.

Trafficability data must likewise be fed into this system because geophysical support in wartime must also cover litho- and atmospheric parameters, since in the majority of cases air raids are conducted in connection with tank operations on the ground.

The input of industrial and urban emission data would substantially improve the reliability of visibility forecasts. Besides, this would offer an ideal opportunity for verifying predictions on the propagation of other suspensoids, for example chemical and biological warfare agents.

On behalf of all NATO partners the area to be covered by geophysical data should be extended beyond the borders of the Federal Republic of Germany. Only in this way can uniform basic information systems be established for the benefit of all concerned who by use of computers (GEOVOR) will enable the assignement of those flight routes and levels presenting minimum flight hazards to the man-machine-system. These optimal areas are identified by S. Uhlig's characterization of "chains of natural regions of relatively favourable weather conditions", Fig. 30 /82/.

This should be the way to keep down the current low rate of the weather factor in flight crashes, Fig. 2. This is of special concern since flight accidents due to weather are among the worst.

By selective use of human engineering like the introduction of multisensor systems and the increased presentation of information by acoustic signals as discussed earlier, an optimal pilot alertness to react can be achieved /83, 84, 85/.

Since the professional interpretation of the great number of data in the near future cannot be done by a robot but only by man who is himself dependent upon geophysical effects, the cooperation between the medical and the geophysical community must be intensified especially with a view to high speed low level flight.

4. DISCUSSION AND CONCLUSIONS

To avoid one-sidedness, the geophysical HSLLF-problems must be discussed considering all the other contributions to the AGARD conference of Lisbon. For this reason the author postponed the concept of this final chapter until cognizance of the other reprints was gained.

It is noticeable that in practically all discussions the importance of the environmental stress was pointed out. If not only the physiological-psychological but also the physical components which have an effect on the Man-Machine-System are considered, the complexity of synergism becomes apparent. This is of special importance when the concept of environmental stress shall include the consequences of all geofactors. These do not only belong to the atmosphere but also to Hydro-, Litho- and Biosphere. Because of the intensity of interaction of the above mentioned spheres in Low Level, the geoscientific problems of the HSLLF can not be considered from the meteorological viewpoint only.

For this reason it is wrong - or at least misleading - to speak of the "all weather capability" of an aircraft. In this respect, P.V. Kulwicki, therefore, has expressed himself very cautiously in the discussion of the flying capabilities of the F16. It can be supposed that also H.M. Archer would like to have understood the "all weather capability" of the Tornado not in the sence of a complete immunity of this aircraft with regard to unfavourable geofactors. Otherwise it is hardly understandable why J.G. Jones has mentioned the terrain and atmospheric conditions at all, in his paper on "Ride-Bumpiness and the Influence of Active Control Systems", which immediately follows Archer's lecture.

The same is true for the many references of nearly all speakers to the multiple geofactors which represent special hazards for HSLLF.

The "15 year Review of the HSLLF-accidents of the Canadian Forces" by R.C. Rud and D.F. Leben, has given the best proof for the accuracy of the thesis that especially HSLLF is influenced to a high degree by geofactors. Accordingly marginal weather "appears to be the one most significant factor contributing to HSLLF-Accidents". Considering that the human factors mentioned by the above-named authors, are also influenced by geophysical factors it is to be concluded that the "all-weather-capability" is merely a futurist idea.

In this respect the references to the work of A.F. Zeller and I.D. Marsch by R.F. Stribley and S.A. Nunneley is of interest. In these one has examined the material of 3 000 accidents of

fighter aircraft of the USAF (accidents examined in Canada = 30) /86/. This extensive statistical material shows that "the environmental heat may make a significant contribution to the accidents".

Stribley and Nunneley have said that the heat stress is often the highest during HSLLF (also in temperate climates). Therefore more attention must be paid to this medico-meteorological problem from the geophysical point of view in the future.

The importance given to these questions by aero-medicine may be judged from the number of lectures in Lisbon dealing with the "thermal stress".

Besides the already mentioned authors also T.M. Gibson, J.R. Allan, C.J. Lawson and R.G. Green talked on these problems. Referring to the important research by R.R. Bollinger and G.R. Carvell they confirmed indirectly the effects of "thermal stress" on the flight-accidents of the Canadian and American AF with data from the UK. According to this data the pilots' errors amount to 24.2 % in summer but only 9.5 % in winter! In a combat situation this means of course, considerable differences in the success of missions.

In order to improve the rate of success it is absolutely necessary, according to the opinion of the Senior test pilot British Aerospace J.J. Lee, to know the "optimal flight path". This can only be indicated under geophysical aspects. If the geophysicist considers in his briefing the exact "cloud cover" and the position of the sun, the choice of a suitable flight-route alone can reduce the thermal stress to a minimum.

Geophysical consultation is all the more important as the technical possibilities of the cockpit-climatisation are still not satisfactory at present as pointed out by Timbal and Colin.

In HSLLF the question of the flight path and the flight altitude with minimal heat-stress is still more important because the g-tolerance can be affected by the temperature (Bollinger et al). Besides, in consequence of sweat dripping into the eyes, there can very often be a considerable reduction of the flight visibility. Of course, thermal-stress can relatively often be expected with VMC. Because of the above mentioned influence on the g-tolerance meteorological aspects must, in "fair weather", lead to flight paths with a minimum of relief energy. Furthermore paths along winding rivers, as for example the Moselle in France and Germany must be avoided.

These indications show that consultations of HSLLF especially under VMC conditions must take into consideration topographical and geophysical Structures. In view of the causality of vibrations P. Quandieu, P. Borredon, J.C. Roumet and L. Pellieux have stressed this demand. The above authors mention further the influence of the geological formations on the air-density in the lowest friction layer, which, as could be demonstrated by the example of the "Plaidter Hummerich", can lead to flight accidents.

In many cases the risk of accident, is increased, also by the turbulences and vibrations occurring at the same time and the visual suppression resulting from it (G.R. Barnes, M.E. Johnston, R.L. De Hart, D.N. Jarrett, L. Vogt, E. Schwartz, H. Mertens, M.E. Johnston, J.H. Wharf). Geophysical consultations to HSLLF must therefore point out the many aspects of CAT near the ground-level.

Since the position of the sun and the weather decisively influences the background-brightness and the illumination in the cockpit, both factors determine at the same time the chance of target-acquisition and the optimal design of cockpit displays. (R.H. Holmes, D.N. Jarrett, H. Rosenwasser, G.T. Chisum, J.J. Kulik, M.L. Wolbash., M.M. Cohen, A. Lewis, D.W. Hossey, M.E. Johnsten, J.H. Wharf, M.A. Ostgaard). Possibly these optical difficulties in the cockpit will contribute to increased use of acoustic signals in the future. In this respect it is important to note that in the 23rd Annual Meeting of the Human-Factor-Society in Boston, Mass. (Oct. 29, - Nov. 1, 1979), which followed the conference in Lisbon, the problem of the "auditory vs. visual display" was subject of a special lecture /87/. In this Fig 31 shows clearly the faster reaction of the proband to acoustical signals than to optical signals. The authors, however, are very cautious with follow up conclusions stressing that the application of the auditory channel must not be regarded as the ultima ratio, because the tone occasionally caused strongest panic reactions (full braking).

Possibly the "Colour Display", discussed by D.W. Hussey in Lisbon represents a new cockpit philosophy, which also satisfies the special demands of a hostile environment.

In any case it is noteable that quite an extensive range of colours is planned for use in the civil transport electronic flight instruments currently under development.

R.H. Holmes emphasized in this respect "that also light aircraft which have dials with coloured segments for normal or caution ranges often have better presentations than military aircraft".

It must be supposed that the developement of the "optimal display technology" will also profit from the geophysical indications of the cockpit environment. The collaboration of the geophysicist in the solution of aviation problems is necessary in any case when it deals with new "Indicative-Technics", e.g. of the wind shear /88/.

These problems must be emphasised from the geophysical point of view, especially because it makes the establishment of priorities possible. The question of the wind shear indication is for example of considerably greater importance for the correct and quick reaction of the pilot than the purely academic question of the influence of spherics.

The lectures in Lisbon as well as the recent publications in the sphere of "human factors" showed, how difficult the determination of suitable parameters for the quantification of the en-

vironmental stress is. Remarkable is for example the agreement of the research of H. Radke and M. Voss/D. Bouis, according to which the puls-frequency cannot be used as a physiological measure for purely sensomotoric stress /42/89/.

The crucial question to geophysics is always "In which way can geophysics make an active contribution to the decrease of environmental stress ?" Here only prophylactic methods are of value. The geophysicist must indicate to the pilot exactly the flight path and the flight altitude, which are most suitable for the solution of his military mission. This can be done best with the aid of the terrain-data-bank, explained in this paper.

The lectures in Lisbon have shown that in addition to the geophysical data already mentioned especially the values of relief energy must be stored. The potential g-forces on the different flight paths could be found with the help of so called "Hypsographs" /90/. Because of the considerable influence of the g-forces on the faculty of the pilot's vision, it is of no use to determine a flight route which shows good meteorological, but poor physical conditions for the pilot.

As the author has shown, an integrated evaluation of the "effective sight", which is decisive for the pilot in HSLLF especially under battlefield conditions must be carried out /91/.

The way chosen by the AWGeophys, namely the use of the terrain-data-bank on the basis of natural regions, is to be regarded as the only right one, as especially the lecture by H. Mutschler has confirmed. It was convincingly shown that the target aquisition is significantly dependent on the contrast values and the local context. A priori one can suppose that the contrast and context values in the "Naturfelder" are equal or similar. This is also valid for the cold season in which a snow cover can be expected which may lead to visual confusion (R.L. De Hart).

Since comparable visual abberiations and apparent displacement of objects caused by shock waves at transonic speeds, compression, or turbulence of air can be expected within a natural region, the geophysical consultation based on these natural regions should be optimal.

The importance of the "Bird-Strike-Hazard" discussed here, has also been stressed by R.L. Dettart for the HSLLF. This is important both for flights over land and sea.

Tactical missions over sea must always take into consideration radar holes caused by the thermic layer of water and air Fig. 32/92/. Besides especially those paths to be preferred which offer the greatest survival chance for the air crew in the event of the accidental immersion in cold water. It has to be considered that maritime areas with water temperatures higher only by a few degrees centigrade, can bring a decisive increase of the "ultimate survival" that M.A.A. Hobbs spoke of in Lisbon Fig. 33/93/. Only if this is taken into consideration the problems discussed by J.H. Raddin, L.J. Specker and J.W. Brinkley, about the "sequenced delaytime for escape from HSLLF-profiles" may be dealt with according to their priority.

The above mentioned author is, by the way, convinced as well as W.Mc Intosh of the importance of the problems of "survival under adverse weather conditions". This statement is not only valuable for sea- but also for land-regions, in which the chances of survival can be extremely different.

As an example the relatively high temperatures of +3° C in the vicinity of "Eskers" can be mentioned, which prevail throughout the entire winter while freezing temperatures of -30° C are common in the surrounding area e.g. in Finland Fig. 34/94/.

It is clear that a pilot near such increased temperatures has a considerably higher chance of survival.

The phenomena described above also occur with certainty in other arctic and sub-arctic areas.

The declaration of the admiral F. Turner, mentioned by M.A.A. Hobbs "we have seats and ejection systems that literally hurl the man out into the darkness" must be extended in the geophysical sence as follows: "the pilot needs geophysical information on the areas, where he has the best chance to survive".

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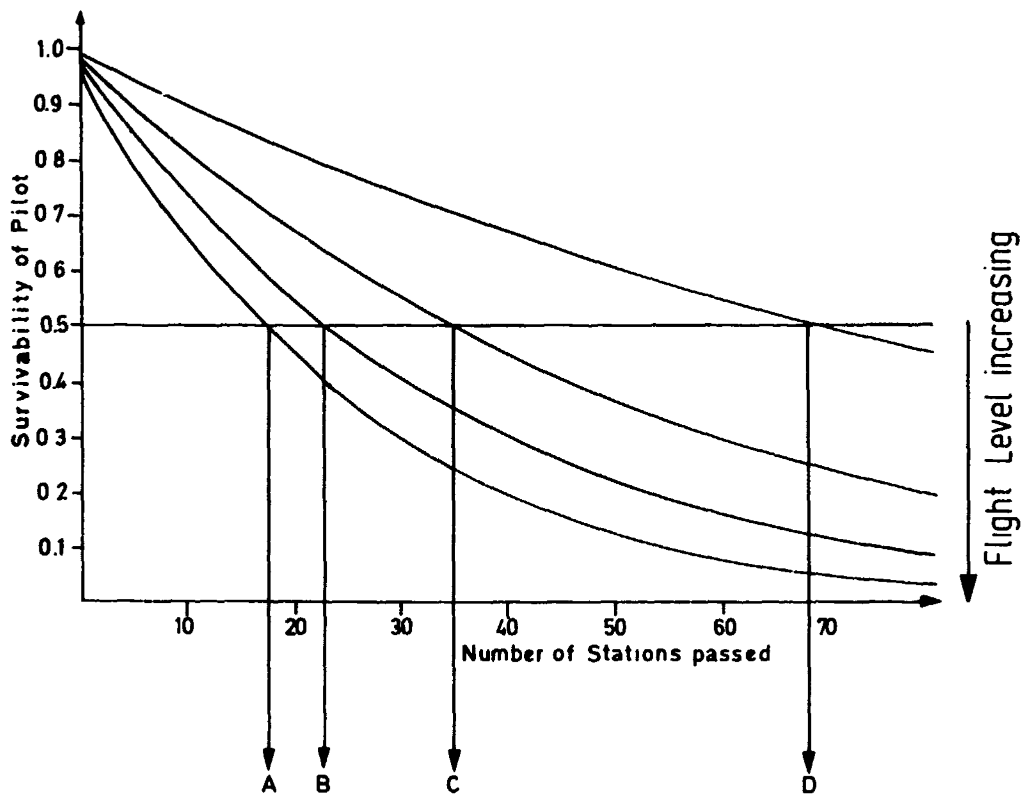
FIG 1



Effectiveness of Air Defense System (A-D) with Repect to Flight Level

Influence of Weather in Percentage on Aircraft Accidents in the Bundeswehr

1965 – 1977

FIG 2

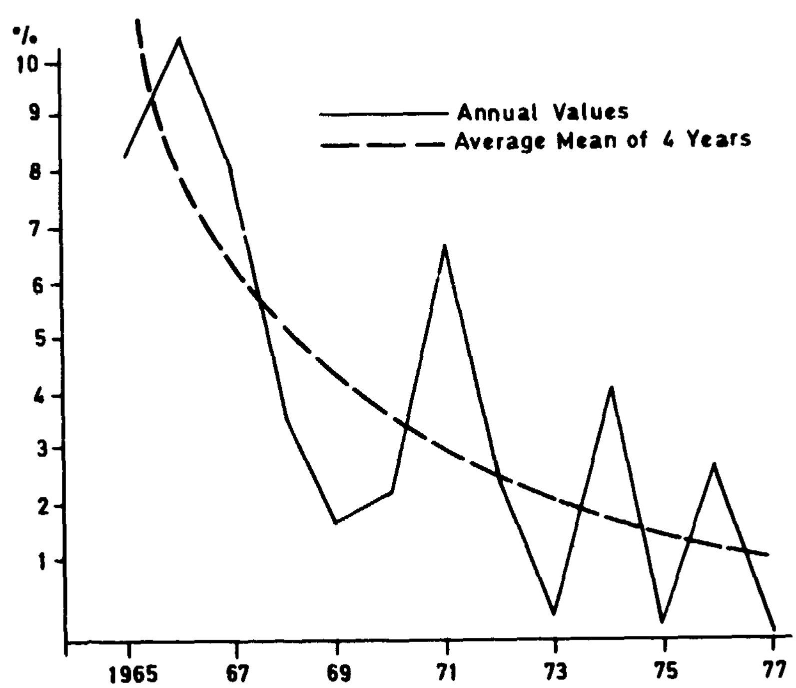
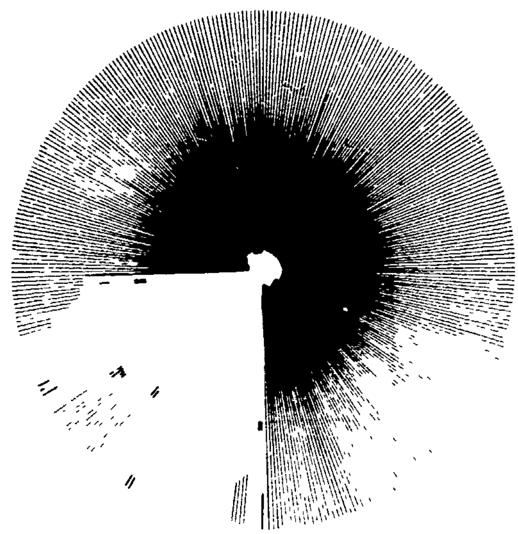


FIG 3 - 7
DIAGRAMS OF RADIAL VISIBILITY, RADIUS OF CIRCLE = 7 km, CENTER = POSITION OF PILOT. SHADED AREAS NOT VISIBLE TO PILOT, INDEPENDENT OF FLIGHT DIRECTION /4/ EXAMPLE FROM SOUTHERN GERMANY

FIG 3



FLIGHT ALTITUDE 150m

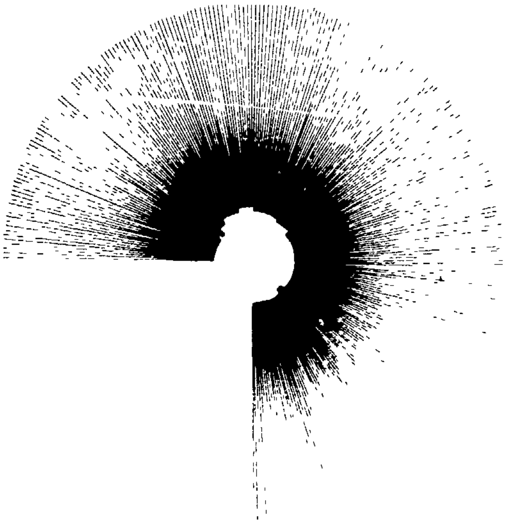
VEGETATION HIGHTS NOT CONSIDERED

FIG 4

FLIGHT ALTITUDE 150m

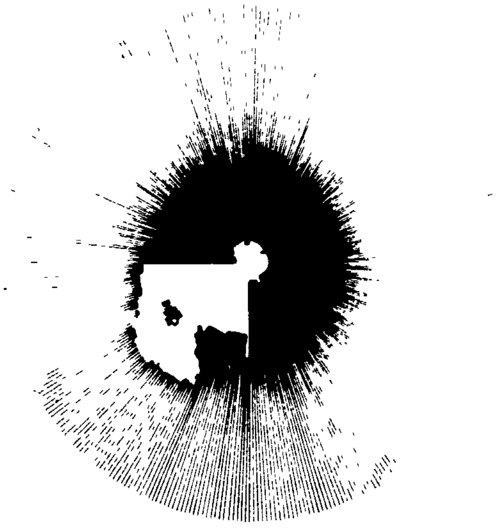
VEGETATION HIGHTS CONSIDERED

FIG 5



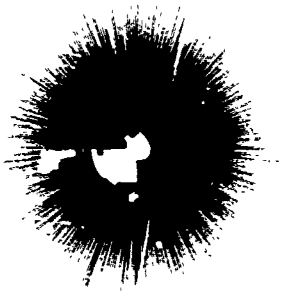
FLIGHT ALTITUDE 500m
VEGETATION HIGHTS CONSIDERED

FIG 6



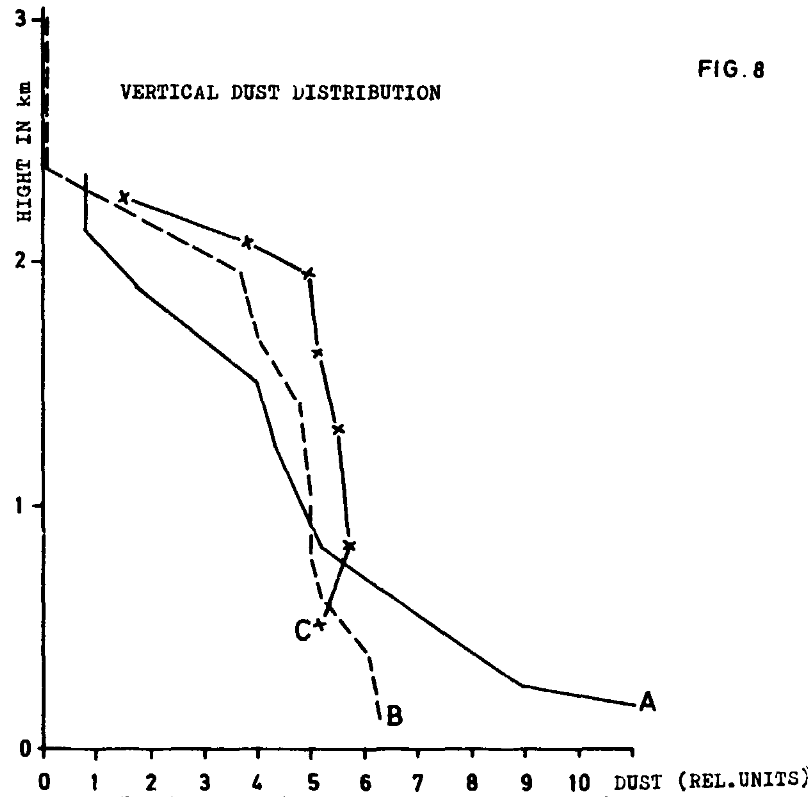
FLIGHT ALTITUDE 150m
VEGETATION HIGHTS CONSIDERED

FIG 7



FLIGHT ALTITUDE 75m
VEGETATION HIGHTS CONSIDERED

FIG. 8



A FORENOON, B, C AFTERNOON OF 27 JULY 1936
THE LIFTING CAUSED BY INCREASING CONVECTION IN THE AFTERNOON IS CLEARLY SHOWN
(Dörfel, K., Lettau, Rötschel, M., Luftkörperalterung als Austauschproblem auf Grund von Staub- u. Kerngehaltsmessungen, Met. Z. (1937) S. 16)

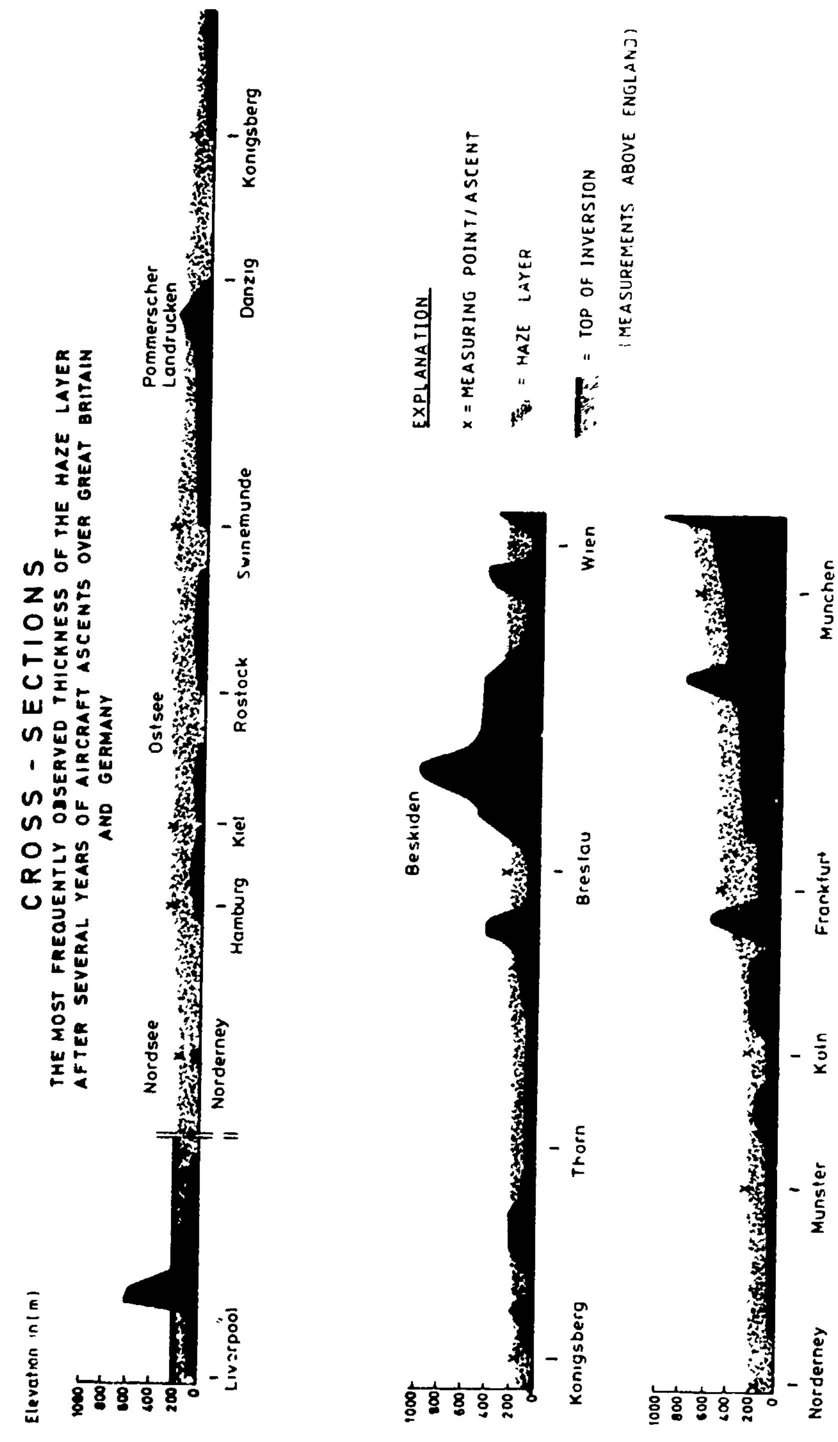

CROSS - SECTIONS
THE MOST FREQUENTLY OBSERVED THICKNESS OF THE HAZE LAYER
AFTER SEVERAL YEARS OF AIRCRAFT ASCENTS OVER GREAT BRITAIN
AND GERMANY
Elevation in (m)
1000
800
600
400
200
0
Liverpool
Nordsee
Norderney
Hamburg
Kiel
Ostsee
Rostock
Swinemunde
Pommerscher Landrucken
Danzig
Konigsberg
Konigsberg
Thorn
Beskiden
Breslau
Wien
Norderney
Munster
Koln
Frankfurt
Munchen
EXPLANATION
x = MEASURING POINT/ASCENT
= HAZE LAYER
= TOP OF INVERSION
(MEASUREMENTS ABOVE ENGLAND)

FIG 9

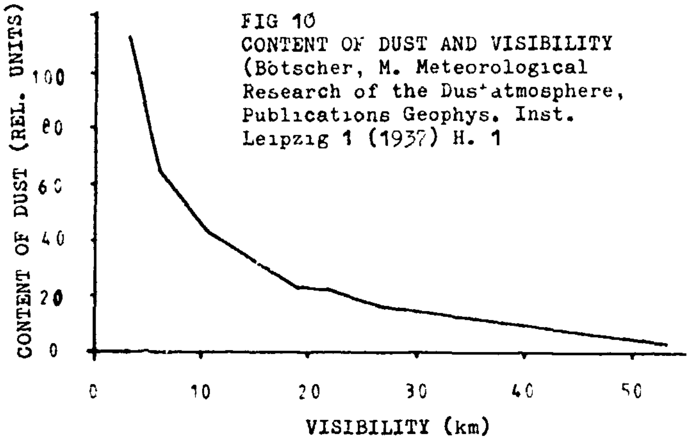


FIG 10
CONTENT OF DUST AND VISIBILITY
(Bötscher, M. Meteorological Research of the Dus*atmosphere, Publications Geophys. Inst. Leipzig 1 (1937) H. 1

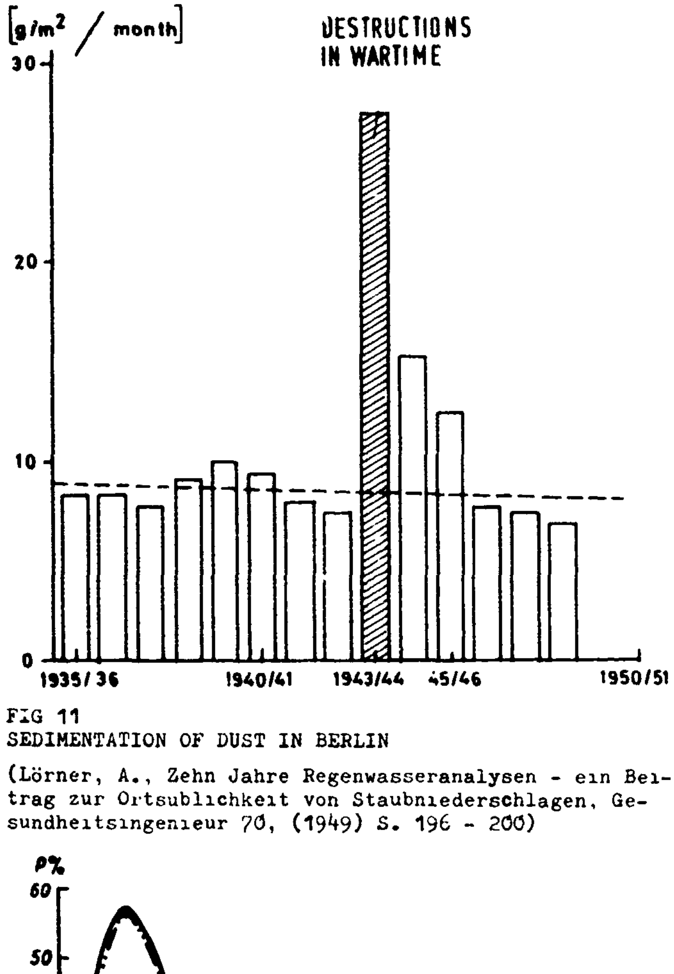
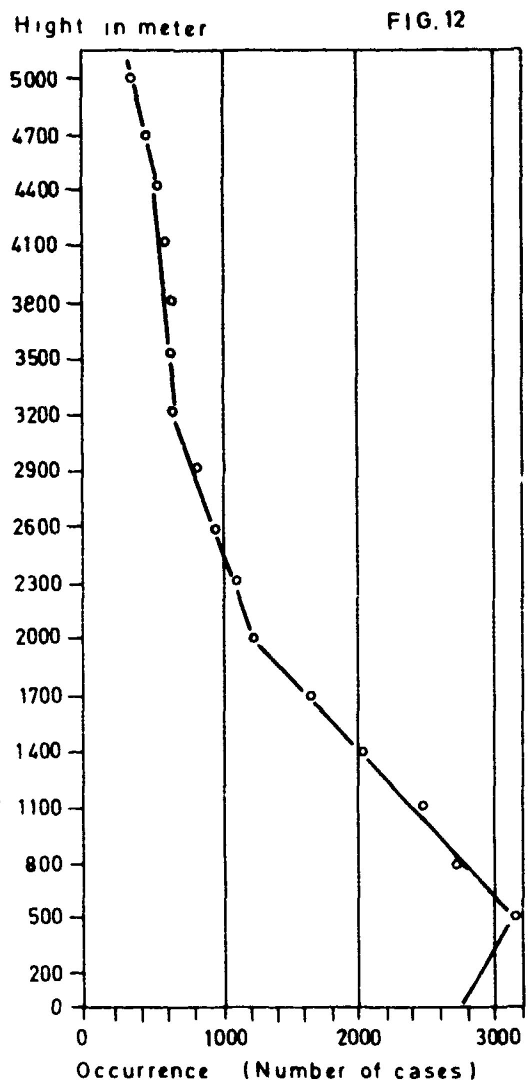


FIG 11
SEDIMENTATION OF DUST IN BERLIN

(Lörner, A., Zehn Jahre Regenwasseranalysen - ein Beitrag zur Ortsublichkeit von Staubniederschlagen, Gesundheitsingenieur 70, (1949) S. 196 - 200)



OCCURENCE OF CLOUDS AND FOG IN HEIGHTS BETWEEN 0 AND 5 000 m, HAMBURG, SOESTERBERG, COLOGNE, MILDENHALL. (Skierlo, U., Statistische Bearbeitung der Wolkenmessungen ausgewahlter europaischer Wetterflugstellen, Forsch. u. Erf. Ber. des RWD, RA Nr 3, 1940)

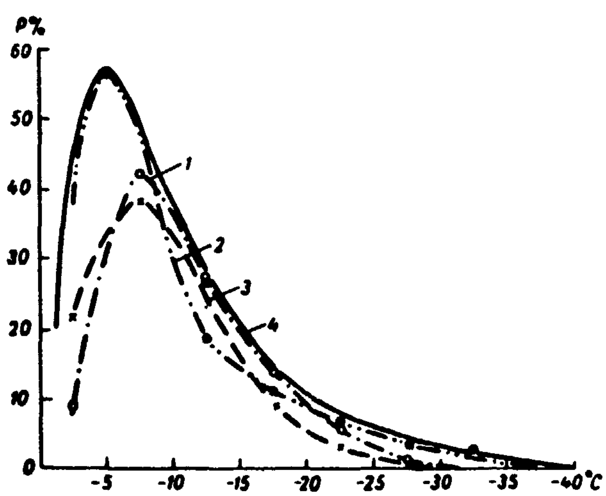


FIG 13
FREQUENCY OF ICING AS A FUNCTION OF AIR TEMPERATURE. (Trunov. O., Zaschtschita ot obledenenija sverchzvykovych samoletov. Aviacija i Kosmonavtika, Nr 2 (1969))
1. 1775 TEST FLIGHTS IN CIVIL AVIATION IN THE USSR - 2. 260 DEBRIEFINGS OF PILOTS OF BOAC AND TU-114 - 3. 220 TEST FLIGHTS OUTSIDE USSR - 4. ENVELOPE

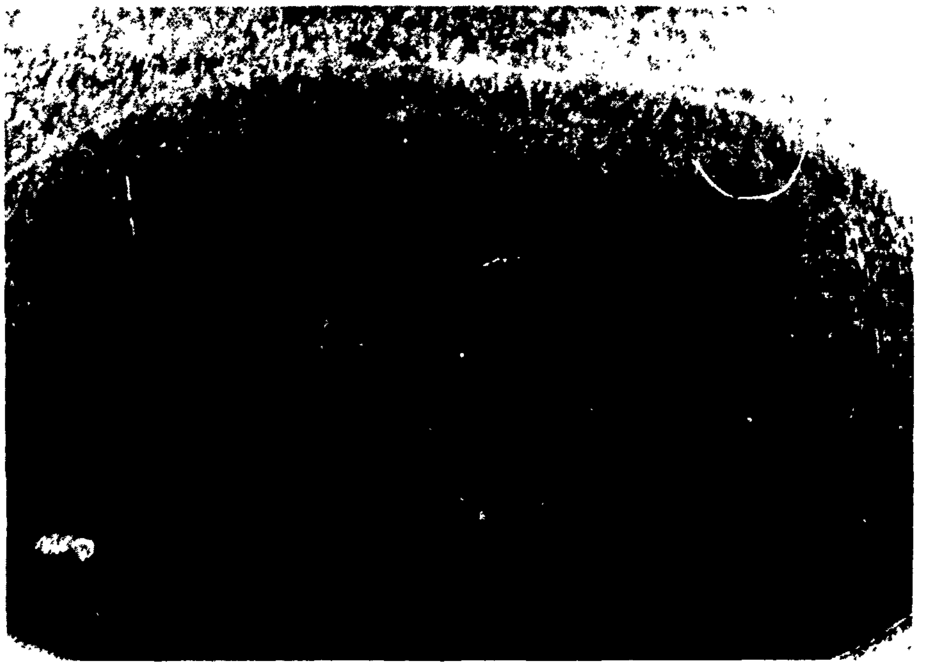


FIG 14
INSECT IMPACTS ON THE COCKPIT OF A BREQUET ATLANTIC, 19.06.1979

FIG 15
INSECT IMPACTS ON THE COCKPIT OF AN ALOUETTE II IN LLF. THE RESTRICTION OF VISIBILITY WAS THE CAUSE OF A SEVERE ACCIDENT. THE HANGAR, DISTANCE 30 m, CAN HARDLY BE SEEN.

FIG 16

SEASONAL VARIATION OF BIRDSTRIKE

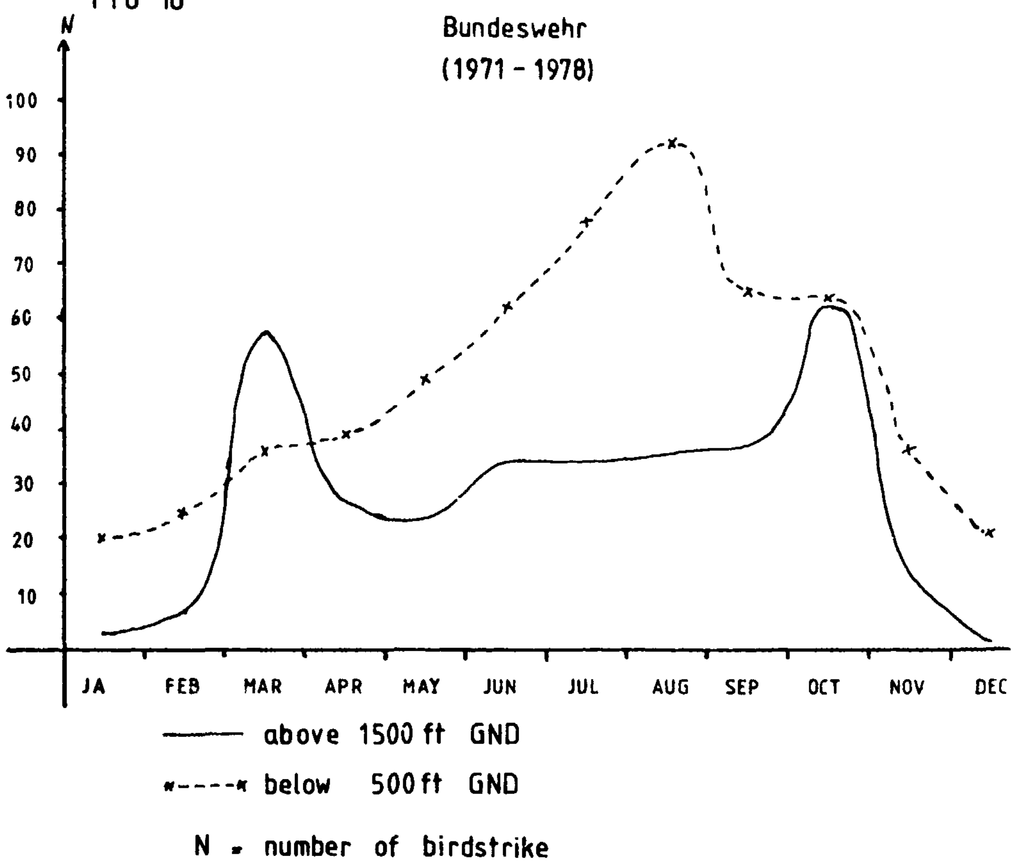
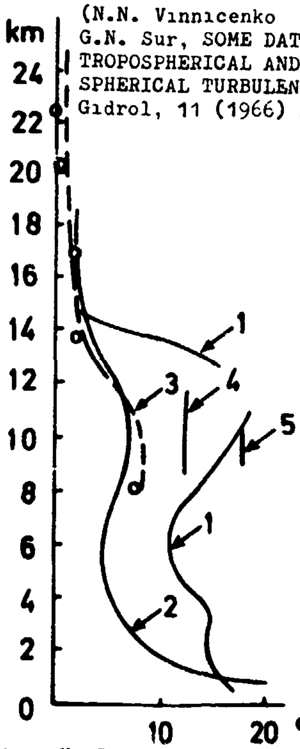


FIG 17
FREQUENCY OF TURBULENCE AS A FUNCTION OF HEIGHT
(N.N. Vinnicenko N.Z. Pinus, G.N. Sur, SOME DATES ABOUT TROPOSPHERICAL AND STRATO-SPHERICAL TURBULENCES, Met. i. Gidrol, 11 (1966) S. 26 - 33)



1. = USSR, SOUTHERN AREA
2. = USA
3. = USA/ U-2-DATAS
4. = USSR MIDDLE LATITUDES
5. = FLIGHT-ROUTES
LONDON - FAR EAST
LONDON - NORTH AFRICA

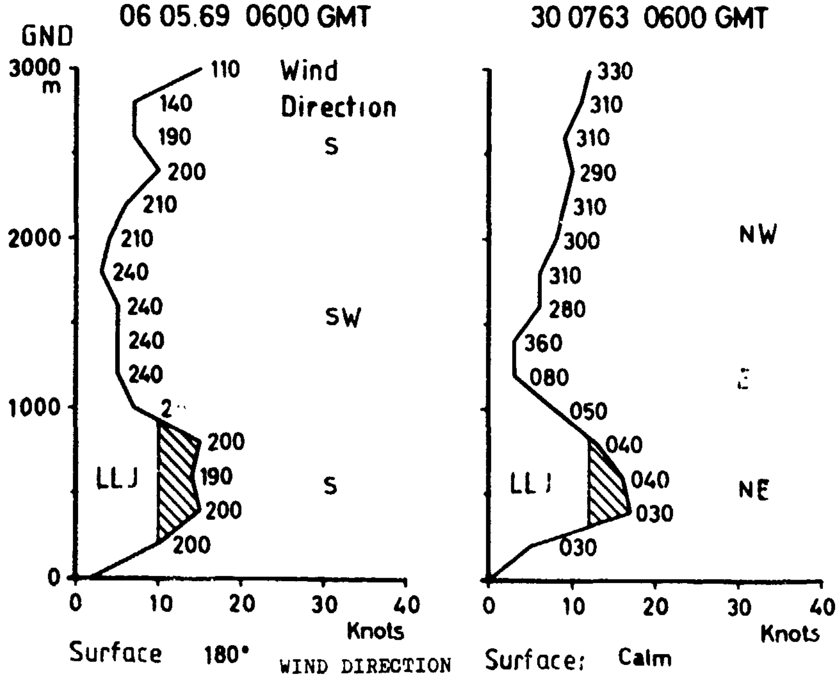


FIG 18
LOW LEVEL JET OVER ALTENSTADT (ALPS, GERMANY) /23/

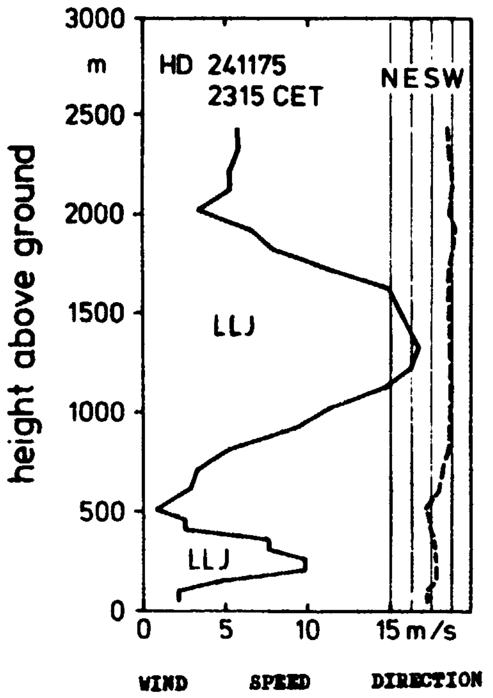
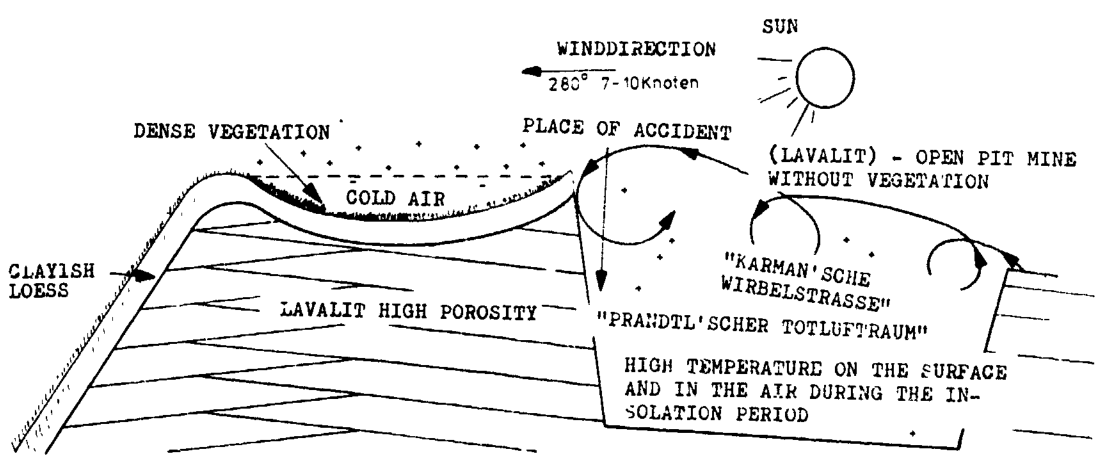


FIG 19
LOW LEVEL JET IN THE BAVARIAN PRE-ALPINE REGION /25/
HEIGHT ABOVE GROUND

FIG 20

FLIGHT ACCIDENT IN THE CRATER OF THE EXTINCT VOLCANO
"Plaidter Hummerich"



THE ACCIDENT WAS CAUSED BY THE HIGH TEMPERATURE
AND DENSITY GRADIENTS NEAR THE POINT OF IMPACT

FIG 21b

CRASHED ALOUETTE II IN AN OPEN PIT BIMSE MINE NEAR PLAIDT, GERMANY

FIG 21a ←

CRASH OF AN AIRCRAFT ON THE RIM OF THE CRATER OF THE EXTINCT VOLCANO PLAIDTER HUMMERICH. A-D MARK THE POINTS WHERE THE VERTOL HIT GROUND IN THE OPEN PIT LAVALIT MINE

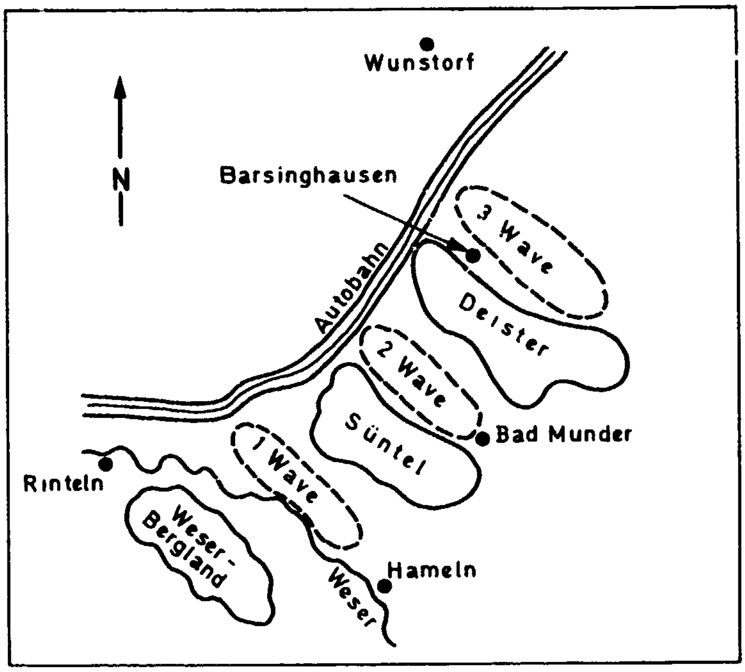
FIG 23a

RELEASE No 72664, Bez. Reg. fur Rheinhessen, BY COURTESY OF Landesbildstelle Rhld.-Pfalz

VOLCANO Kunskopf, Germany

FIG 23 b Diatomit = highly porous sceletons of fossil algae with very low coefficient for heatconduction

FIG 24



Waves caused by Orography South of Hannover

|33,34|

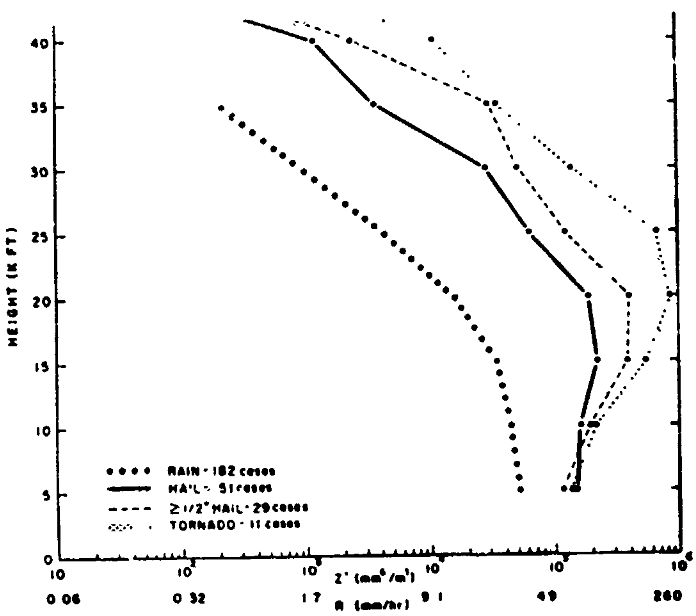
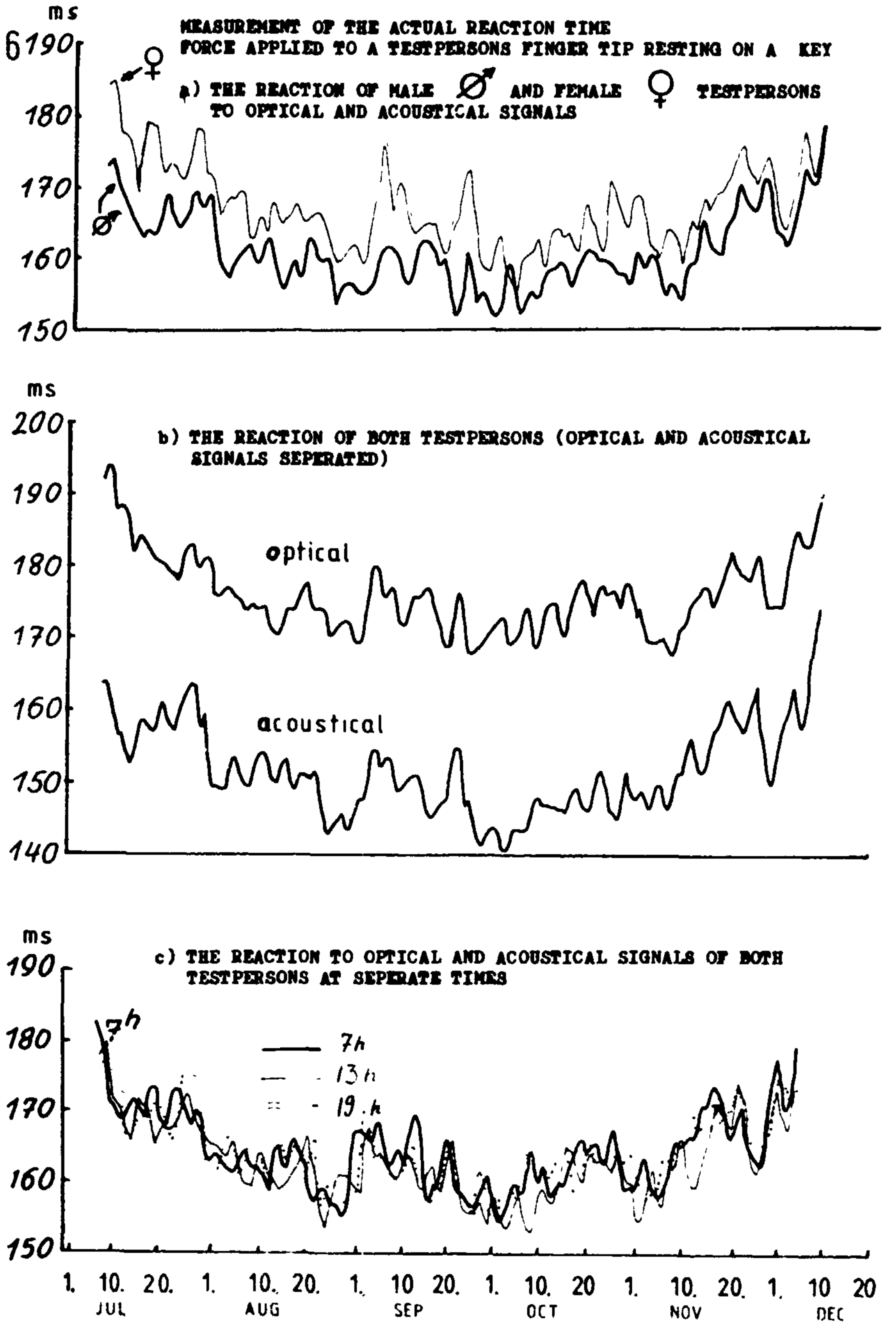


FIG 25
AVERAGE PROFILE OF THE REFLECTIVITY FACTOR Z
IN THE CENTRE OF THUNDERSTORMS
(1957 - 1958 IN NEW-ENGLAND)
(BY R.J. DONALDSON, JR.)

FIG 26

|39|


ms
MEASUREMENT OF THE ACTUAL REACTION TIME
FORCE APPLIED TO A TESTPERSONS FINGER TIP RESTING ON A KEY
a) THE REACTION OF MALE ♂ AND FEMALE ♀ TESTPERSONS
TO OPTICAL AND ACOUSTICAL SIGNALS
190
180
170
160
150
ms
200
b) THE REACTION OF BOTH TESTPERSONS (OPTICAL AND ACOUSTICAL
SIGNALS SEPERATED)
190
180
170
160
150
140
optical
acoustical
ms
c) THE REACTION TO OPTICAL AND ACOUSTICAL SIGNALS OF BOTH
TESTPERSONS AT SEPERATE TIMES
190
180
170
160
150
7h
7h
13h
19 h
1. 10. 20. 1. 10. 20. 1. 10 20. 1. 10. 20 1. 10. 20. 1. 10 20
JUL
AUG
SEP
OCT
NOV
DEC

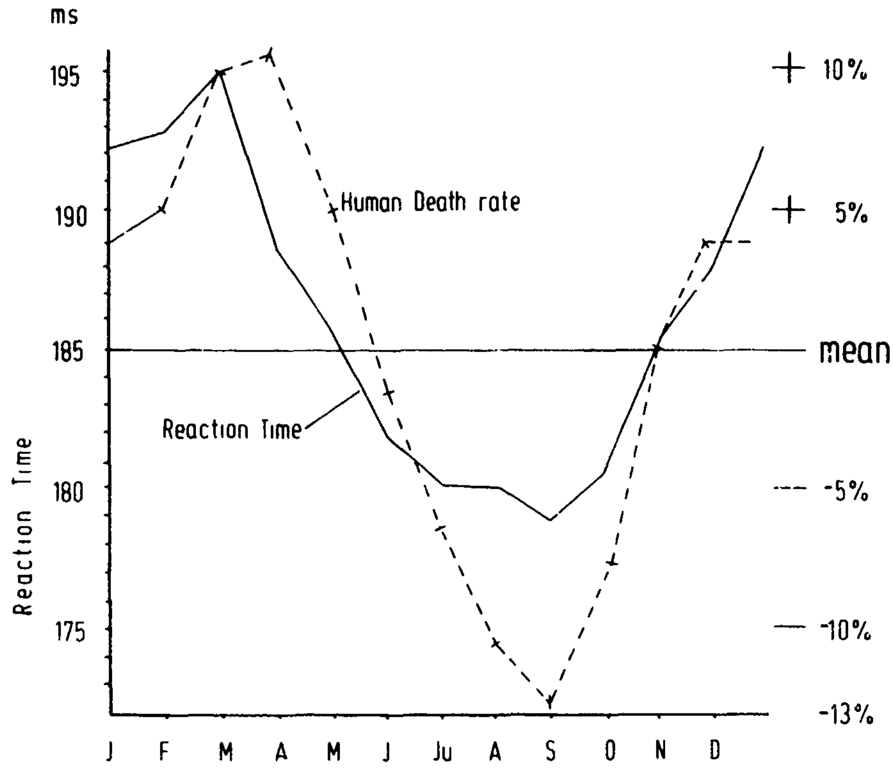
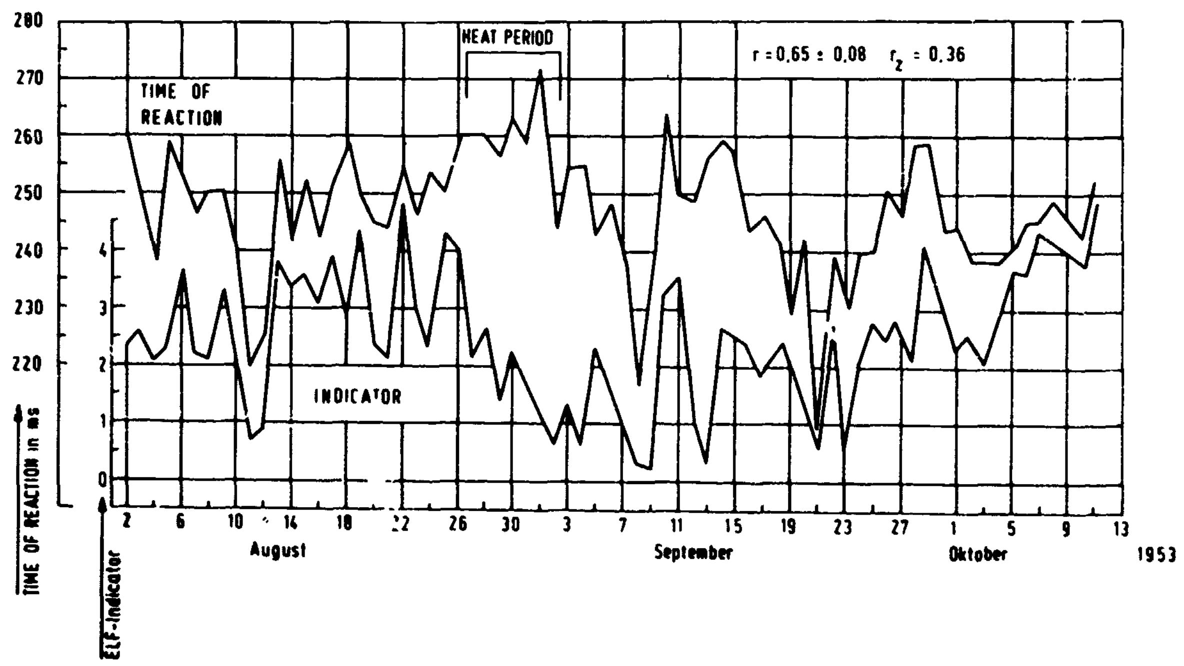


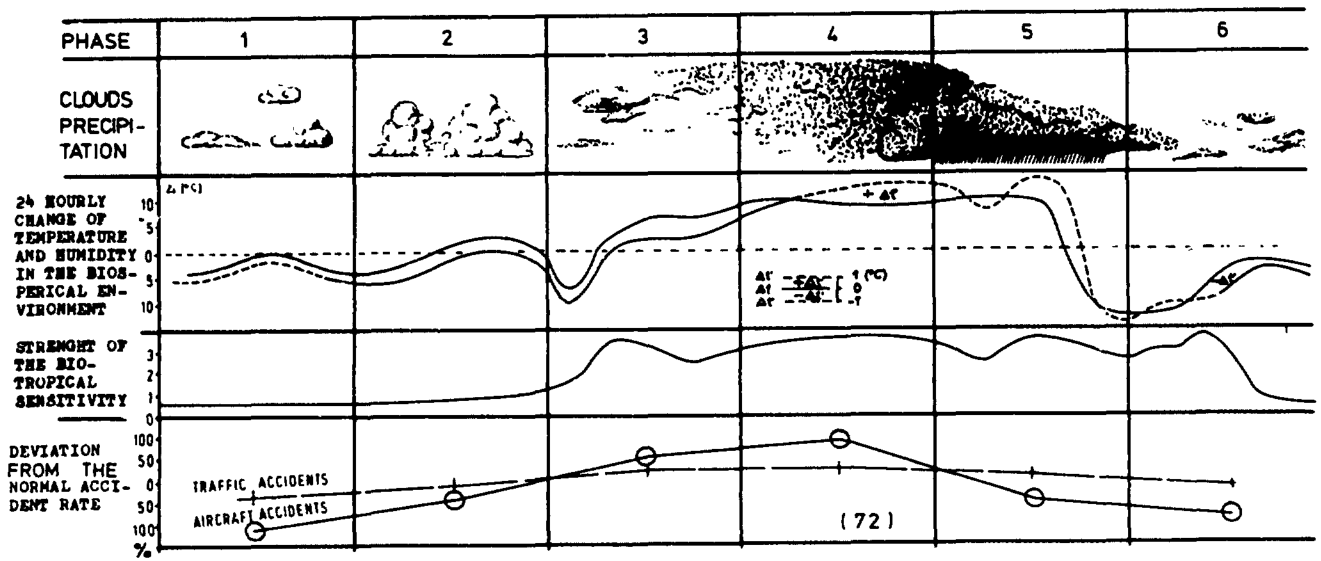
FIG 27 ANNUAL VARIATION OF HUMAN REACTION TIME
(50 000 TESTS DURING 10 YEARS IN TUEBINGEN) -
OF HUMAN DEATH RATE -
(DEATHS IN 1950 IN SOUTHERN BAVARIA)
THE CONFORMITY OF BOTH CURVES IMPLIES ENVIRONMENTAL
INFLUENCES /44, 45/

DIAGRAM OF TIME OF REACTION AND ELF (SPHERICS) WITH 40 000 PERSONS BEING TESTED, 118 300 INDIVIDUAL MEASUREMENTS /45/ — FIG 28

ELF = Extremely Low Frequency



DEPENDENCE OF THE FLIGHT AND TRAFFIC ACCIDENTS ON WEATHER PHASES 1-6 (FRONTAL PASSAGE)



STATISTICAL DATA: 42724

TRAFFIC ACCIDENTS 1950 - 53

(Spann, W. Verkehrsunfälle und Wetter Med. Meteor. Hefte 11 (1956) 152)

AIRCRAFT ACCIDENTS DURING A TWO YEAR PERIOD

THE INCREASE OF ACCIDENTS HAS ALREADY BECOME APPEARANT BEFORE THE FRONTAL PASSAGE (PHASE 3)

THE CAUSAL RELATIONSHIP WITH ENVIRONMENTAL STRESS IS GIVEN ONLY WHEN THERE IS EQUAL TRAFFIC FLOW IN EACH OF THE 6 PHASES

FIG 29

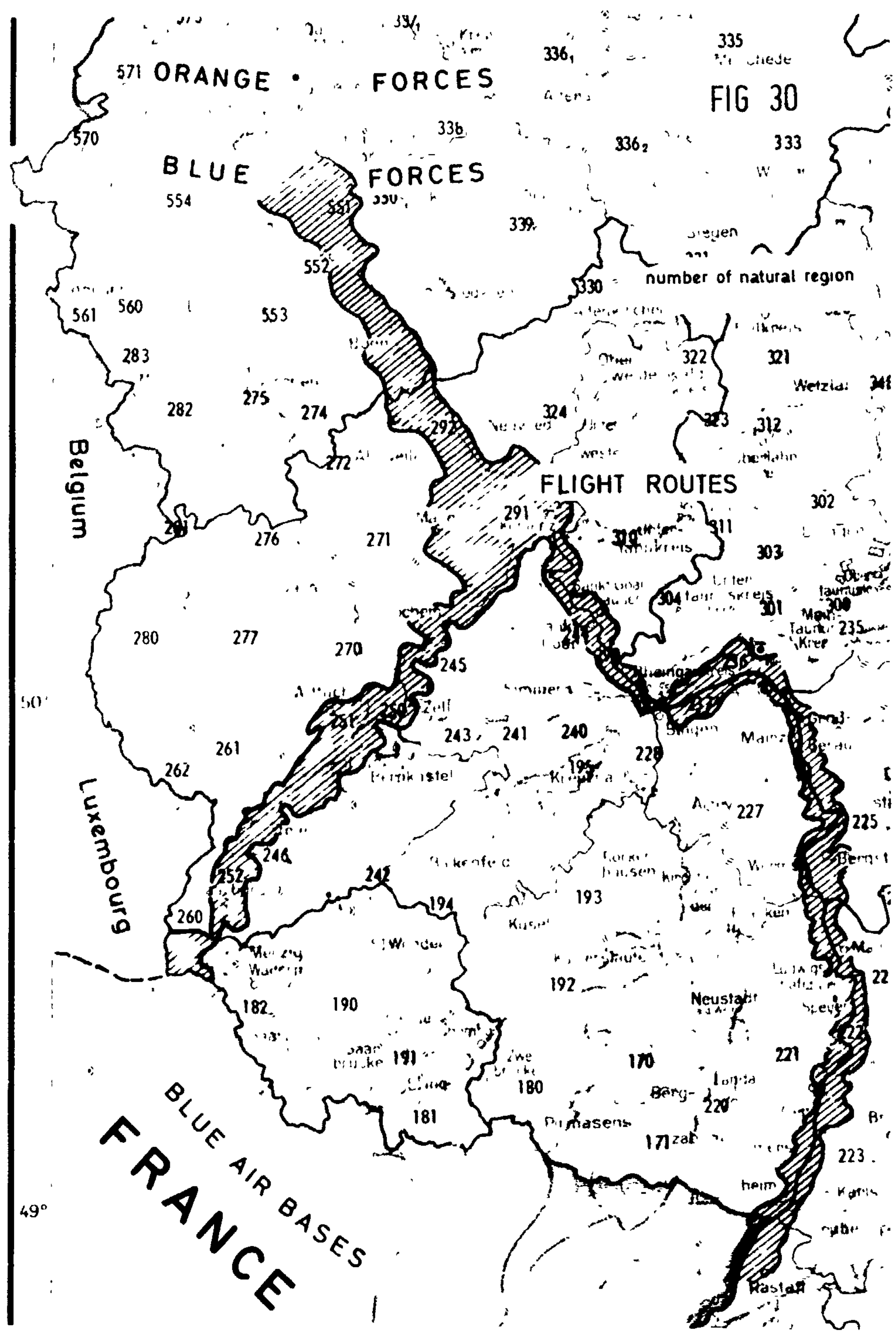


FIG 30
SCHEMATIC DIAGRAM OF OPTIMAL FLIGHT ROUTES USING THE "NATURRAEUME" CHART BY MEYNEN (UHLIG CHAINS) WESTERLY MOIST AIRFLOW MILITARY SITUATION ASSUMED: ORANGE FORCES IN KREFELD - DUESSELDORF AREA - BLUE FORCES IN THE SOUTH - BLUE AIR BASES IN EASTERN FRANCE - THE OPTIMAL EFFECTIVE VISIBILITY RANGE (TOPOGRAPHICAL AND METEOROLOGICAL) IN NW + NE DIRECTION OCCUR IN THE DELINEATED AREAS UNDER THE ASSUMED WEATHER CONDITIONS. (K. KRAMES, INTEGR. BEWERTUNGSMODELL FUER SICHTVERHALTNISSE IM RAHMEN DER STUDIE FÜR ENDPHASENGELENKTE PANZERPROJEKTILE, AWGEOPHYS. INTERNER BERICHT 79/48, SEPT. 1979)

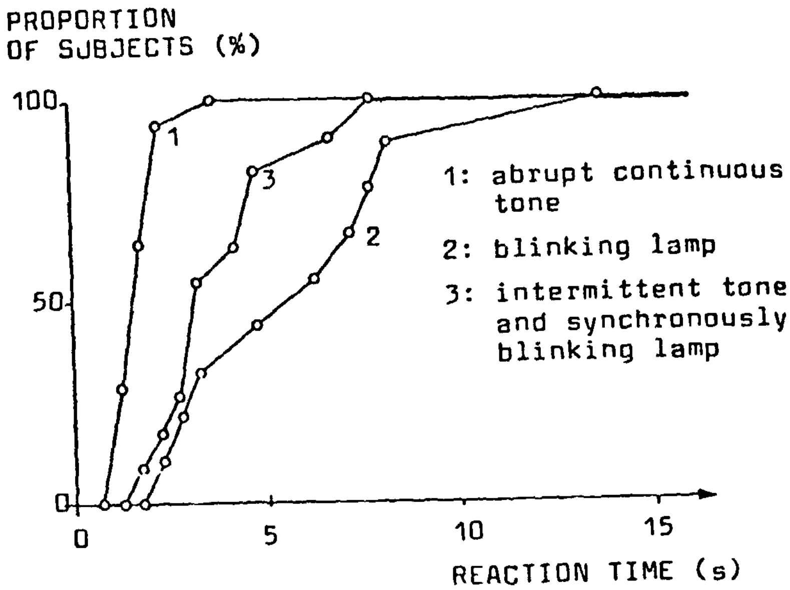


FIG 31 /89/ Proportion of subjects which have reacted versus time for different types of displays.

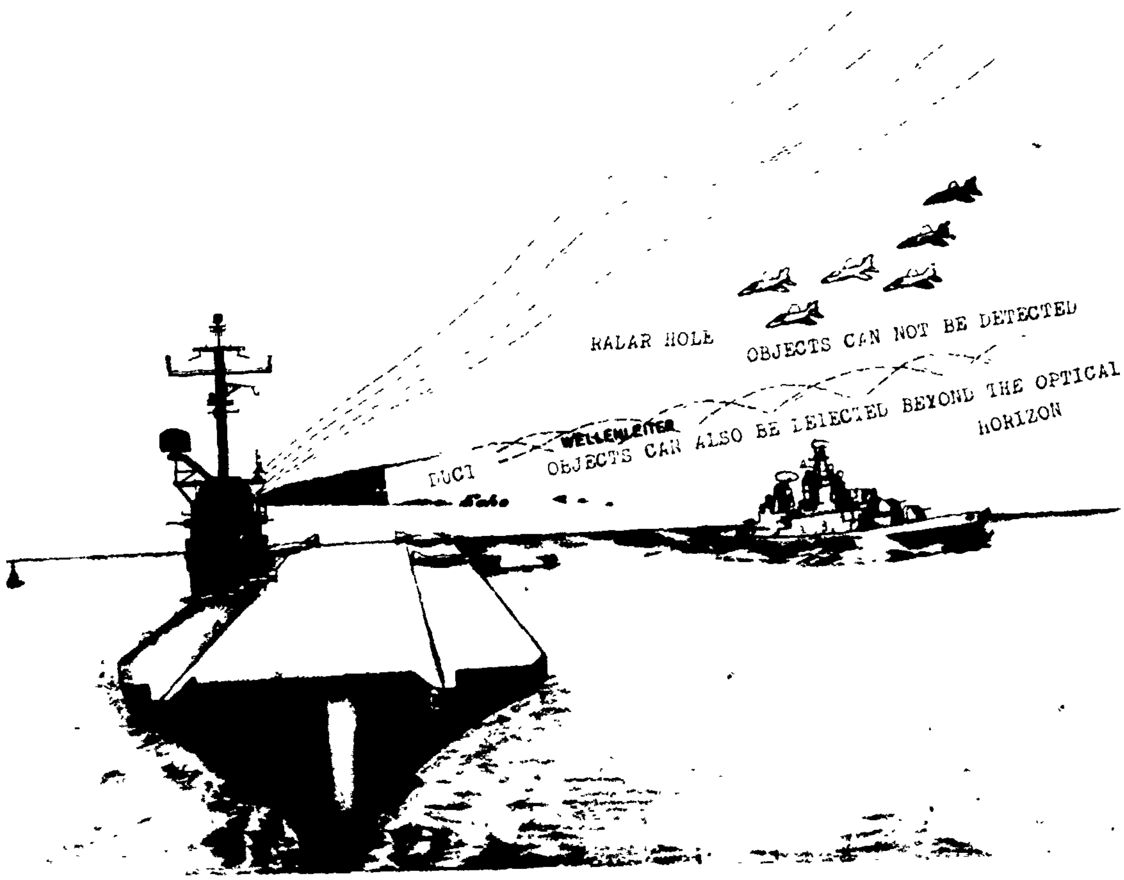


FIG 32
THE DUCT-PHENOMENA CLEARLY DETERMINES THE ALTITUDE OF THE ATTACKING AEROPLANE

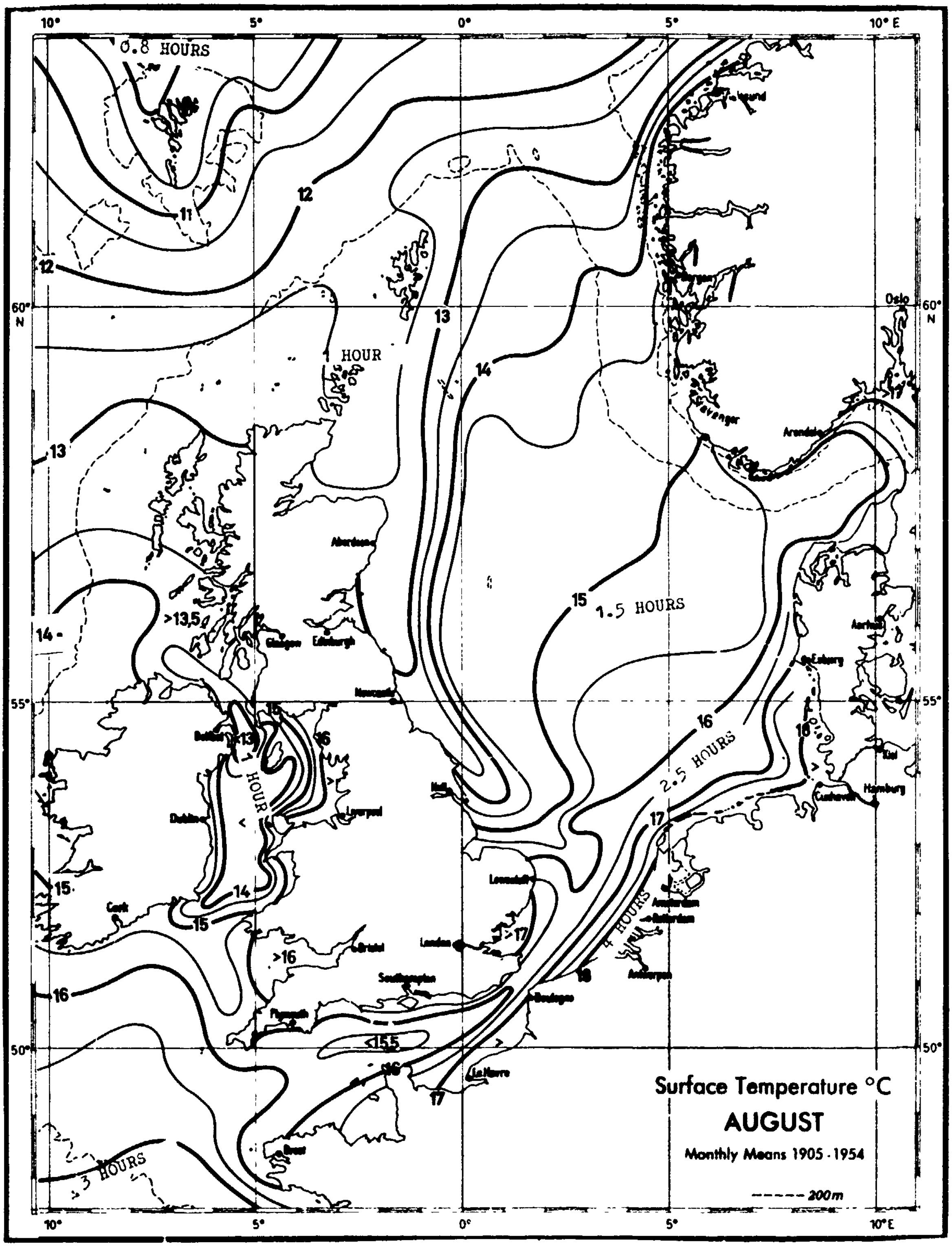


FIG 33a
PROBABLE SURVIVAL TIMES V/S IMMERSION TIME IN WATER
(MEAN MONTHLY TEMPERATURE AND SALINITY OF THE SURFACE LAYER OF THE NORTH SEA AND ADJACENT WATERS FROM 1905 to 1954, CONSEIL PERMANENT INTERN. POUR L'EXPLORATION DE LA MER SERVICE HYDROGRAPHIQUE CHARLOTTENLUND SLOT, DANEMARK 1962)

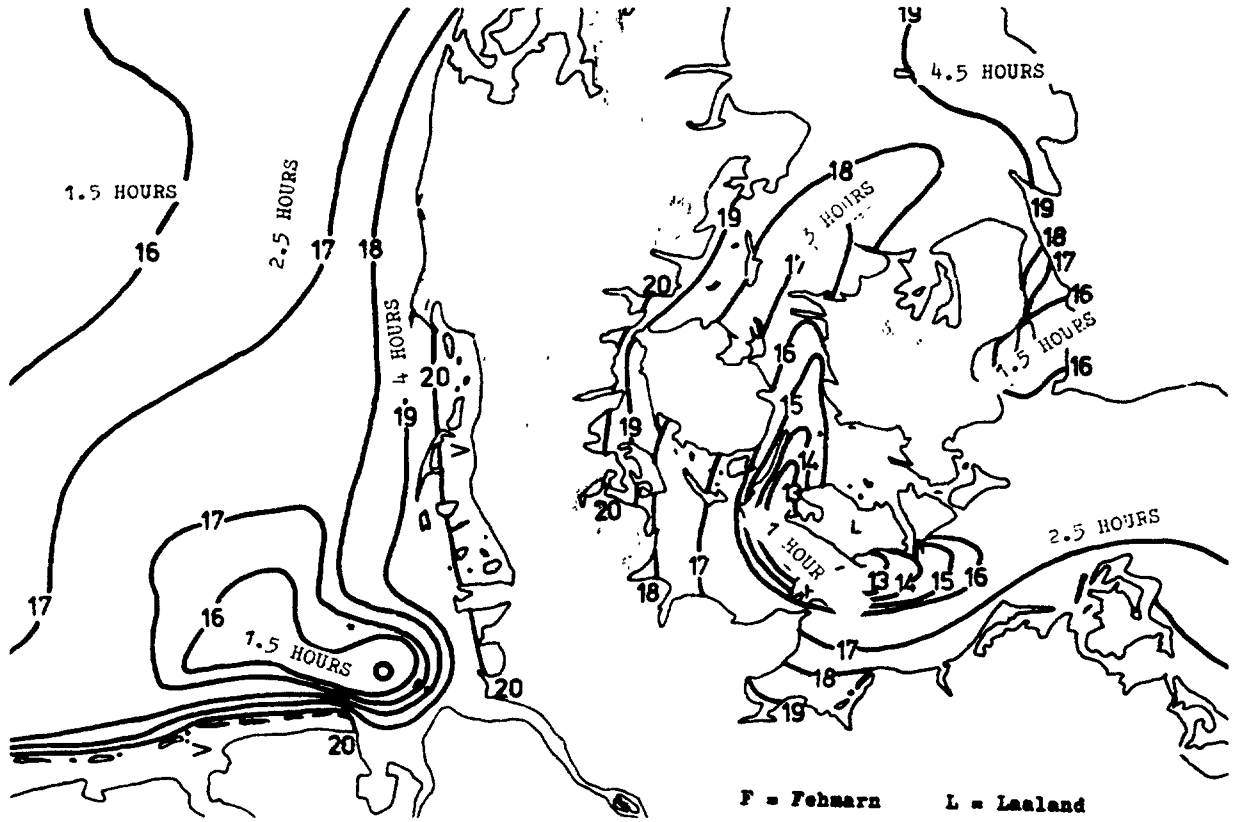


FIG 33b PROBABLE SURVIVAL TIMES V/S IMMERSION TIME IN WATER (03.08.1978) SURFACE TEMPERATURE ° C
IT IS POSSIBLE TO RECOGNIZE SIGNIFICANT DEVIATIONS OF MONTHLY MEAN
THEREFORE THE GEOPHYSICAL FORECAST HAS TO CONSIDER ACTUAL WATER TEMPEPATURES

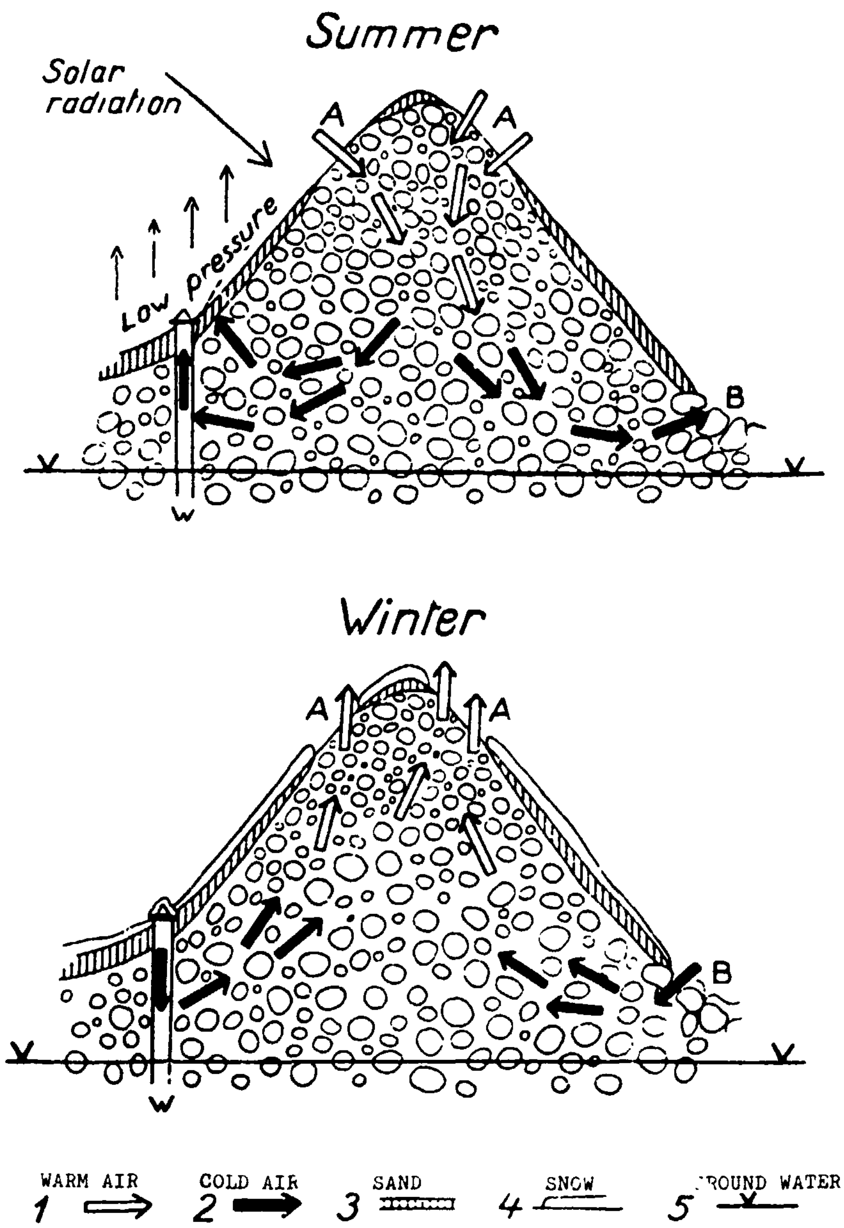


FIG 34
ESKERS, i.e. DEPOSITS OF THE ICE AGE IN SUB-ARCTIC AREAS
WARMTH WHICH IS BEING STORED DURING SUMMER WILL BE SET FREE IN WINTER, THUS INCREASING TEMPERATURE ABOUT MORE THAN 30° C AND PROLONGING SURVIVAL TIMES /94/95/

Development in High Speed Low Level Flight - The Pilot's Viewpoint

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Preston, Lancashire PR4 1AX, UK

Introduction

In the nineteen sixties there was a school of thought which stated that 'the fighter aircraft had not changed significantly since the Second World War'. Being a pilot on a Hunter Ground Attack Squadron at the time, a role which almost exclusively included flight at high speed and low level, the sagacity and truth of this statement seemed particularly poignant. This school of thought became silent, perhaps extinct in about 1975.

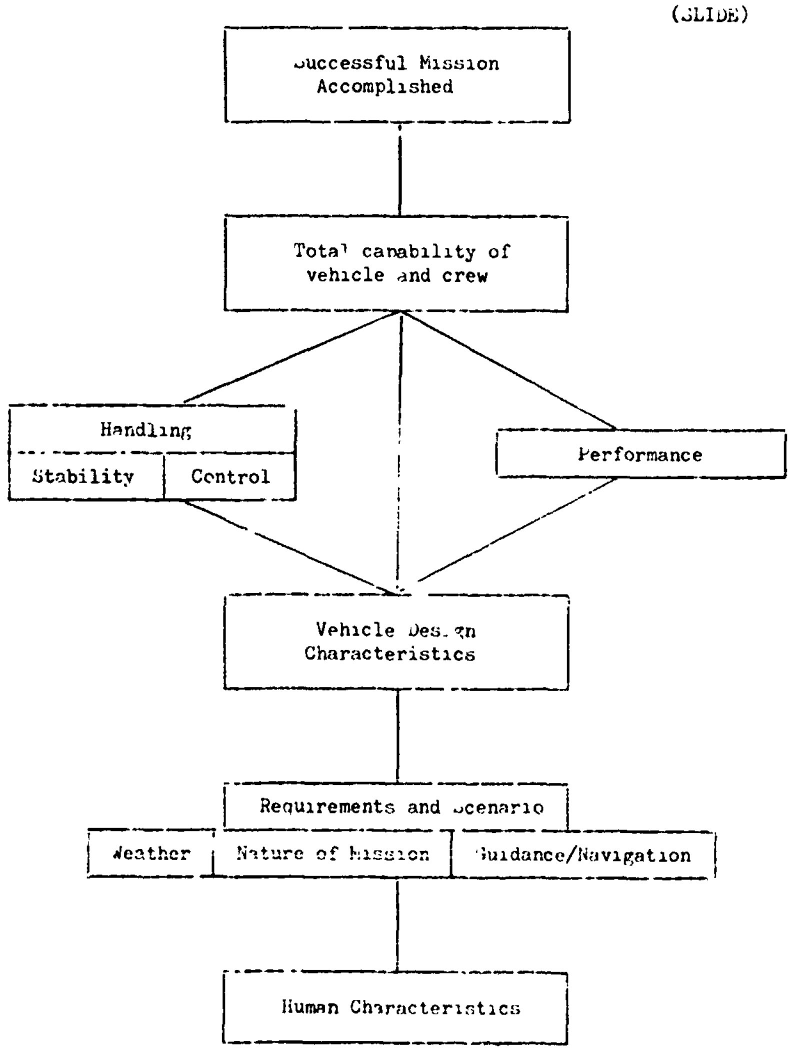
To a large extent the Hunter represented the last of a breed which did, in fact, fulfil the essence of the stated hypothesis. Its basic equipment fit, its armament and weapon aiming system had changed little, if at all, from the days of the Spitfire and Mosquito. It could, however operate in the high speed low level role very effectively within certain constraints.

The Tornado, an aircraft development for service in the 1980s, represents a new breed developed for flight at high speed low level, having amongst its roles exactly the same close support mission as the Hunter. A comparison between the two aircraft and their equipment can be made to illustrate the problems associated with operating aircraft at high speed and low level, and how developments in technology have overcome or minimised them. In so doing the school of thought so active and widely heard until the late sixties, is finally silenced and consigned to history.

Mission Success

Mission success is of course of paramount importance and at high speed and low level the problems are most acute. The situation can be summarised diagrammatically:-

(SLIDE)



It should be noted that this schematic of aircraft and crew characteristics will fit any aircraft in any role, but let us look at the aircraft specifically in the high speed and low level role. At the bottom there is the block labelled Human Characteristics which includes sensitiveness to stimuli (tactile, visual and aural), reaction time, strength/stamina and resistance to fatigue, and adaptability. Indeed adaptability has frequently been responsible for successful mission accomplishment in the low level role in the face of poor handling, performance and air vehicle design characteristics. Pilots and crews have put up with a degree of discomfort to achieve mission success, but there is an important borderline between discomfort and distraction sufficient enough to jeopardise mission success or aircraft safety. Fatigue has too taken its toll in the hot, bumpy, noisy, high workload environment of high speed low level flight.

Looking further up the schema to requirements and scenario, in which the global nature of the task is covered, in this case the example of offensive support at high speed and low level in the European theatre is used, with the obvious influence of weather and navigation/weapon guidance upon the way in which the mission can be carried out.

Air Vehicle Design Characteristics describe the nature of the aeroplane, whether it is STOL, number of engines (safety criterion) number of weapon carriage stations, the type of navigation/weapon aiming system, fixed or variable geometry, gust response, one crew or two etc.

Handling, divided classically into stability and control, and performance complete the description of the aircraft/crew package and describe the total capability. This total capability will establish the success of the aircraft in its role and the limitations that will have to be taken into account in military service operations in order to accomplish a successful mission.

Human Factors

In the limited time available I should like to choose three factors which relate directly to the limitations in human characteristics in aviation terms, which enter into different categories on the block schematic. These are:-

Weather

Terrain Following Flight

Aircraft Handling

A comparison will be made between the Hunter and the Tornado to show the advances that have been achieved in each case.

Weather

Visual Metereological Condition (VMC) of 5n.ml (9km) (defined as a minimum) visibility and vertical separation from cloud of 1500' max more or less defined the flight conditions in which a mission could be accomplished in an aircraft like the Hunter. With practice at low level flight the pilot could do a little better, being able to navigate and more important, visually acquire the target, in a visibility of $5\frac{1}{2}$ km, provided that he limited his speed to 360kts (11km/minute) to give himself time to recognise the terrain or the target.

One important reason for the constraint in visibility was the lack of essential head-up orientation cues. With a Head-up Display as shown having a velocity vector presentation, vertical speed, altitude, speed and heading the pilot only has to refer head down for fuel management and engine and system monitoring. The HUD allows flight to be possible over land up to 500kts in a visibility of $5\frac{1}{2}$km. At 16km per minute the pilot has to be certain of what is coming up ahead, and the limit of the human characteristics of recognition/reaction time is reached.

Altering the format of the HUD to this sort of layout as in Tornado can improve basic safety and ease the flying task. The counter-pointer altimeter presentation gives an analogue/digital height scale which is more compulsive than a line of digits.

To improve mission capability a further aid is required, and this is terrain following radar.

Terrain Following Flight

Flight at high speed low level requires high concentration and intensive training. It is a lengthy costly exercise to train pilots to fly at low level simply to judge the altitude at which to fly. The high concentration results in loss of lookout (awareness of other aircraft proximity, be they friend or foe) a reduction in time available to navigate, or to keep formation.

Operational aspects such as radar detection avoidance (avoidance of ballooning over ridges and cols, avoidance of climbing in turns) require the learning and practice of special flying techniques in what is essentially already a high workload environment.

Let us see some film taken from a Hunter-type aircraft over Scotland.

Any help that can be given to the pilot to reduce the workload by providing a simple altitude cue, an optimum flight path over the ground contours and if possible achievement of this optimum profile by automatic pilot must be beneficial. The Tornado provides a full autopilot and flight director system (AFDS) operating through a terrain following radar.

During automatic terrain following the TF computer generates a theoretical envelope in front on the aircraft. This envelope is shaped like a ski toe and its exact shape and offset from the aircraft will depend on the selected clearance height, aircraft speed, 'ride comfort'.

Terrain detected penetrating this zero command ski toe locus will cause the TF computer to pass a nose-up command, proportional to the degree of penetration, to the autopilot, which in turn passes it onto the fly by wire control system. Alternatively if the terrain is detected well below the zero command locus, a pushover command is generated proportional to the distance below the zero command line.

Let us now look at some film showing the system in action. The pilot can fly the aircraft manually by following the Head-up Display flight director, or monitor the autopilot operation which centres the director dot.

This is a tremendous aid to the pilot, relieving him of the most significant work load. It also provides an all weather and night capability.

To set a pilot's mind at rest, if this is at all possible in IMC or night low level high speed flight, aircraft handling must be of the highest order and thoroughly consistent throughout the flight envelope. This leads to the third factor.

Aircraft Handling

The application of powered flight controls to an aircraft like the Hunter reduced the physical strength required by the pilot to handle the aircraft to reasonable proportions. A basic conventional control system even with autostabilisation cannot provide consistent handling qualities at all CGs and in all configurations. Alteration in CG leads to a change in pitch inertia, stick force per g and pitch response characteristics. Loading stores onto the wings leads to increased roll inertia, reduction in roll response and roll power and perhaps imposes extra limitations on handling.

The pilot would prefer consistent handling and aircraft behaviour and this in Tornado is provided by the fly-by-wire control system incorporating the principle of manoeuvre demand. About all axes and at all loadings the pilot obtains a consistent control response and rate. The slide shows maximum roll rates in stores configurations as a function of Mach Number and wing sweep.

The fly-by-wire system guarantees that the aircraft will always handle in a predictable way, will be consistent, and in this way workload is reduced to a minimum.

Summary and Conclusions

Great strides have been made in aviation technology during the last $1\frac{1}{2}$ decades leading to significant benefits to high speed low level flight. The aim has been, and should always be, to improve the possibility of accomplishment of a successful mission. In essence the 'Human Characteristics' of sensitiveness to stimuli, reaction time, strength/stamina and adaptability have remained virtually unchanged in evolution terms and will no doubt, at normal mutation rates, be very much the constant at the bottom of the equation. Given the requirements of the mission and the scenario, the areas where development can be applied to improve mission success still further remain firmly in the fields of Performance, Handling, Guidance/Navigation and that catch-all heading 'Vehicle Design Characteristics'.

BIOTECHNOLOGY CHALLENGES PRESENT IN OPERATIONAL HIGH-SPEED LOW-LEVEL FLIGHT

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USA

SUMMARY

Currently, the United States Air Force is operating aircraft requiring exacting crew performance in the highly stressful environment of High-Speed Low-Level (HSLL) flight. The strategic role of the B-52 in avoiding surveillance radar requires a mission profile of low level operation. The F-111 performing its tactical and strategic roles employs terrain-following techniques similar to the B-52 but with the important technical difference of automation control. A third mission scenario requiring HSLL flight involves the new tactical support aircraft, the A-10, in its principal anti-armor role. Little information has appeared in the aeromedical literature in the past five years concerning operational stressors in this flight regime. Interviews with operational crews flying these missions, observations from the aeromedical teams supporting the crews, and current research investigations relevant to the stresses of these flight regimes form the data base upon which this paper is based.

INTRODUCTION

Aircrew performance in the aerospace environment is recognized as a demanding task. The most demanding flight regime requiring constant vigilance, rapid but measured control input, and adaptability to a wide variety of environmental stresses is High-Speed Low-Level (HSLL) flight. Such demanding flight profiles are not new to the military aviator. Missions requiring relatively low level flight and the maximum speed available of the day have been required of the military aviator since the 1920s. More demanding flight regimes in terms of critical time to respond to dynamic changes in the environment were evident during World War II when combat aircraft flew in combat at altitudes below 100 feet terrain clearance at speeds approaching 350 knots. Following WW II, aeromedical interest waned with regard to consideration of the HSLL flight regime. Approximately two decades ago, with the concern for survivability of strategic aircraft in high-threat radar surveillance environments, multi-stress effects on aircrew performing in sustained HSLL flight again became an interest of the flight surgeon. This ebb and flow of medical interest for the concerns of the aviator in this demanding flight environment is clearly evident with review of recent aeromedical literature. In the mid-1960s concern for the aircrew members on a typical low level B-52 or B-58 flight sparked numerous publications related primarily to various aspects of vibration. Other publications addressed the problems of fatigue, manual control, visual acuity, and thermal loading in HSLL flights. Medical investigations addressing this type of mission began to wane by the early 1970s. A review of the aeromedical literature for the period 1972 through September 1978 revealed a sparsity of references primarily addressing aeromedical problems associated with HSLL flight.

Currently, the United States Air Force is flying a variety of combat aircraft requiring exacting crew performance in the highly stressful environment of HSLL. The strategic role of the B-52 in avoiding surveillance radar requires a low level mission profile. The F-111 and FB-111 perform tactical and strategic roles employing terrain-following techniques similar to the B-52 with the important technical difference of automation. A third mission scenario requiring high-speed low-level flight involves the new tactical aircraft, the A-10, in its principal anti-armor role, a potentially high stress combat environment. Although each aircraft may impose singularly unique stresses on its crew, there are general similarities common to the overall HSLL mission.

THE COMBINED STRESS

In a review of this subject in 1971, it was stated: "The basic problems in low altitude, high speed flight do not center around life-threatening environments or psychological stress clearly affecting the crewmember's performance as the control center of the weapon system." With the experience of HSLL missions in the intense, threat, combat environment of North Vietnam, the validity of the statement must be questioned, and considering operational exercises involving the A-10 the question of a life-threatening environment and its direct and indirect effect on man as the control center of the weapon system becomes a major concern. Mere observation establishes that the aircrew member's task becomes ever more demanding with increasing speed and decreasing altitude and with the growing complexity of the weapons system he must operate. The margin for error is ever-narrowing while simultaneously the probability of operator overload increases. The adequacy of man-machine integration has never been more tested than in the current case of sophisticated aerospace weapons systems operating in the narrow flight envelope of high-speed, low-level flight under combat conditions.

Numerous stressors, both physiological and psychological, impair the crewmember singly or more commonly in combination. It is important for the aeromedical specialist to appreciate the single stressor, yet more important is the synergism and interaction of these stressors as they act on the crewmember to produce combined stress compromising the opportunity for optimal performance. Some aircraft are flying mission profiles for which they were not originally designed and consequently the environmental control system is inadequate to meet the thermal load of low altitude. Sustained in-flight temperatures in excess of 43° Celsius have been measured at crewstations. The requirement for constant vigilance reduces the opportunity for fluid intake, thus increasing the chances for subtle dehydration when the crewmember is experiencing prolonged thermal loading. Meteorological and topographical conditions can combine to produce significant turbulence translated as buffet or vibration biodynamic force acting on

the aircrew member. Both the aircraft and crew experience vertical and lateral acceleration components in this turbulent environment. Although cockpit acceleration spectra contain little energy above 10 H_z, gust levels ranging from .2 to 2.2G are frequently experienced. Although not common in the strategic mission, linear acceleration can be a stress of some magnitude in the tactical environment. Commonly, linear accelerative forces of 5 to 7 G, with up to 5 G per second onset repeated many times over 30 minutes, are experience by crewmembers in A-10 operations. Linear acceleration combined with gusts and vibration reduce human tolerance to combined accelerative forces. Vibration further induces a number of unfortunate side effects such as difficulty in reading and interpreting instruments, inability to accurately conduct map navigation, compromising verbal communications, and serving as a major contributor to motion sickness. To this already complex combined stress envelope, the aircrew member may be required to contend with overall sound pressure levels at the crew position in excess of 115 dB. Within this complex stress environment, the aircrew member is expected to perform precisely, innumerable tasks related to weapons systems. In one case, 32 individual control or selection tasks must be performed within 180 seconds in a combat environment. In addition, the aviator is expected to maintain outside vigilance for enemy aircraft, ground defense systems, targets of opportunity, navigation way points, friendly forces, both in the air and on the ground, and all of this in a visual environment reduced by haze, smoke, and clouds. Thus we see the a crewman forced to perform ever more precisely and skillfully in an environment which compromises all of his senses, diminishes his powers of concentration, overloads his cognitive ability, and reduces his physiological tolerance.

OPERATIONAL CONDITIONS AND AEROMEDICAL CONCERNS

The stressors described impinge on the crewmembers of the B-52, the FB-111, and the A-10 in varying degrees, differing not with regard to the flight envelope per se as much as in the characteristics of the aircraft, the crew-station, and the mission. (At this point in the presentation a silent 3-minute film will be shown illustrating various aspects of the operational characteristics of each of the three aircraft under consideration. The first segment of the filmstrip will show the B-52 on a low level mission experiencing moderate buffet and turbulence. The second filmstrip will be an out-the-window view of an automatic terrain-following flight of an FB-111. The third segment will contain protions of the JAWS-2 exercise involving the A-10 in its low altitude anti-armor tactical role. The three segments are film clips which have been taken from full-length narrative films which are cleared for public release.)

The Air Force has its greatest experience in the high-speed low-level flight regime with training missions of B-52s perfecting radar avoidance techniques. The aeromedical concerns of this aircraft's flight profile and its effects on the crew is the first topic with which we will deal. Although the avionics suite aboard the B-52 varies with the model, the training flight profile for HSLL is essentially the same. Typically the terrain clearance altitude is 500 feet during daylight operation and raises to 800 feet in non-mountainous terrain at night. Airspeed is maintained between 325 and 350 knots with a low altitude leg duration of 1 to 2 1/2 hours. These parameters define the training envelope but it must be realized that under operational conditions the permissible altitudes may very well be lower and the speeds where feasible higher. Currently the B-52 employs an electro-visual terrain avoidance system that depends on manual control of the flight by the pilot. The navigator maintains obstacle clearance responsibilities using both radar and precision tracking on navigational maps. Aeronautical hazards such as tall structures, radio antennas, and power lines must be avoided employing way-point navigation. The radar operator uses the greater range of his scope for general navigation permitting a 15-20 mile sweep ahead of this flight regime and consequently thermal control in high heat environments is poor. Heat loading consequently contributes to fatigue, discomfort, and potential dehydration. Increasing the ram air to improve air circulation concomitantly increases significantly the cabin noise level. Flights in hilly or mountainous terrain or in areas of wide temperature differential can result in moderate vibration and gusts. Sudden aircraft excursions of $\pm$15 feet are not unusual; thus the crew must be tightly restrained by seat belt and shoulder harness. Missions are normally aborted in severe turbulence, defined as uncontrolled aircraft movement. Mission cancellations may occur in situations where 40 knots or higher winds are reported in mountainous areas. During periods of high vibration the navigator is unable to read a typical aeronautical chart and must depend solely on the radar display. The physical workload on the pilot and co-pilot can be extreme in the constant battling to maintain narrow altitude tolerances.

High thermal loads, vibration, and attempts to read aeronautical charts contribute to motion sickness. In the past this has been a particularly significant problem in B-52 navigator wastage. A significant reduction in wastage due to motion sickness has been achieved by reducing the time lag between navigator or electronic warfare officer training and subsequent assignment to crews. This permits tolerance established during training to be transitioned directly into operational crew duties. Interview techniques employed with B-52 crews as well as monitoring the intercom channel clearly establishes increased tension, irritability, and anxiety among the crew during HSLL missions. The crew recognizes the thin margin for error, and as a consequence communications remain strictly business. The psychological stress operating minimum altitude clearance of 400 feet for parachute deployment, a luxury which very well might not be available. The toll of this multi-stress environment on the crew can best be placed in context when compared to a high altitude mission of similar duration. Universally, crewmembers interviewed described the HSLL mission leg as far more fatiguing.

The mission of the FB-111 may parallel that of the B-52. However, the crew composition and cockpit environment are significantly different. The FB-111 flight profile under usual conditions is typically 400 feet at .63 to .73 mach (420-480 knots). At nighttime, in non-mountainous terrain, the altitude will approach 1000 feet. Unlike the B-52, there is a totally automated terrain-following mode for the FB-111. Typically, the on-board radar will identify changing terrain features 10 miles in front of the aircraft's track. At six miles the computer will calculate the dynamics of the flight path; at two miles from the change in terrain feature, the aircraft controls will automatically react. The terrain-following system is displayed such that constant monitoring is possible. In addition to the terrain-following radar display, the aircraft's pitch and roll may be superimposed for instant reference. To

supplement the visual presentation, audio indications are available to the pilot. During climb there is both an increasing frequency of beeps and an increasing tone. The frequency of beeps is proportionate to the rate of climb. Likewise during descent the frequency decreases as does the tone. The two-man crew is constantly task-loaded: the right-seater performing navigation checks and way point estimations; the left-seater monitoring aircraft performance and maintaining vigilance on the terrain-following system. Universally, crews cited the need for even more automation of the aircraft's system to permit heads-up, out-of-the-cockpit surveillance. In a high threat combat environment the pilot must maintain outside visual surveillance and reference. Improvement in the automated terrain-following system by increasing the permissible bank angle from 10^o to 30^o has improved both the survivability and the flexibility of the weapon system. The aerodynamic features and the speed of the aircraft both contribute to reduce the vibration-induced stress on the aircrew and it is not considered a problem of consequence. Crews on occasion have experienced disorientation resulting from the confusion of ground lights and star background. Crew familiarity with this hazard through briefing appears to be an effective preventive measure. Another feature of night missions not previously identified leading to visual confusion, disorientation, and possibly flicker vertigo is reflection of the anti-collision strobe light from highly reflective ground surfaces such as snow. A hazard to the FB-111 crew which has resulted in aircraft loss and fatalities has been birdstrike. The Air Force currently has mustered a major program to solve this problem. In the interim, the crews brief birdstrike procedures prior to each HSLL mission. Simply stated, in case of a birdstrike and the loss of the windscreen, the terrain-following automated feature of the aircraft will be engaged until such a time as the aircraft can be decelerated and the situation analyzed. This is perhaps the most complimentary statement to be made regarding the automated terrain-following feature. Crews praise the reliability of the system and are confident of its performance. Significantly, night flying missions are more precise and are considered less dangerous. This appears to be due to the dependence on the automated system and cross-reference with the altitude radar rather than visually misjudging altitude above the ground. The heads-up display is reported as satisfactory; however, there are times when excessive information is portrayed. This can result in clutter on the combining glass, reducing see-thru. The environmental control system for the cockpit is excellent and excessive thermal loads have not been experience in operations even in the southwest United States. Structurally the cockpit has poor outside visibility. It is difficult for the crewmember to have full right-to-left and down viewing. The location of some of the dials and switches such as the air conditioning system and the IFF require the pilot to turn his head in order to operate. This can be particularly hazardous during angular acceleration and could contribute to coriolis. Excessive operation of the master caution light usually triggered by exceeding the terrain-following system limits requires the pilot to look back into the cockpit to resolve the problem and may lead to momentary but significant distraction. It is a common opinion among the FB-111 crews that the mission is at minimum a two-man job and workload and task performance would be overwhelming for one individual.

Low altitude operation of the A-10 in its tactical mission is of short duration but of intense work-load. The aircraft is frequently below 100 feet, flying between 200 and 300 knots. In performing a tactical mission 40% to 60% of the time will be spent under 500 feet. A typical mission from takeoff to recovery will be 1 1/2 to 2 hours. During a recent sortie surge exercise, six tactical missions per day were flown for a period of 3 days. The cockpit environment is comfortable in terms of thermal control and acoustic isolation except in areas of high heat load. Although the main fire power of the aircraft is a large Gatling-type cannon, vibration and noise are at a minimum. The cockpit layout with regard to instruments and controls is adequate although the heads-up display is limited by field of view. Figure 1 illustrates a typical flight profile for a training mission. The graph portrays airspeed, altitude above terrain, accelerative forces, and flight duration. The high threat environment, low altitude, and high maneuverability as exemplified by a 1300 foot radius of turn dictates that the pilot maintain a vigilant eyes-out-of-the-cockpit, heads-up posture. It is imperative for successful missions and for general safety that information required by the pilot be presented in a format not requiring his attention within the cockpit. Information formatting could be oral or visual. Realistic training conducted in marginal weather conditions has demonstrated the need for an inertial navigation system, freeing the pilot from the current high task-loading requirements of navigational pilotage.

DISCUSSION

It has been previously reported low altitude high speed flight does not involve problems of physiological tolerance but rather alterations in pilot effectiveness through overload and response to a general stress syndrome, increasing fatigue with increasing periods of exposure. Vibration, at one time ranked as the primary stressor on the aircrewman performing HSLL missions, has now become less a concern as different aircraft enter the inventory and the mission of low level flight changes. The popular concept that pilots were unwilling to relinquish control to automatic systems can now be delegated to history as the systems become proven with experience and earn the confidence of the aircrew member.

There exists a common technology need requiring contributions from the aerospace medical practitioner which becomes evident in discussing the aircraft in their respective HSLL combat missions. Continued development of automated systems integrating components within the cockpit affecting aircraft controls and weapons delivery systems is required. The specialist in aerospace medicine must ensure that sophisticated systems do in fact offload peripheral tasks of the pilot and increase his performance and ability to successfully accomplish the mission in a high threat combat environment. In addition, it is evident opportunities are available for biotechnology to improve or develop systems providing required information to the aircrew member in a method or format which permits him to remain heads-up and eyes-out-of-the-cockpit. The mission requirements are clear. Aircraft survivability dictates a low level flight envelope. The aeromedical community is charged with the obligation to widen the margin between safety or disaster, mission success or failure, victory or defeat.

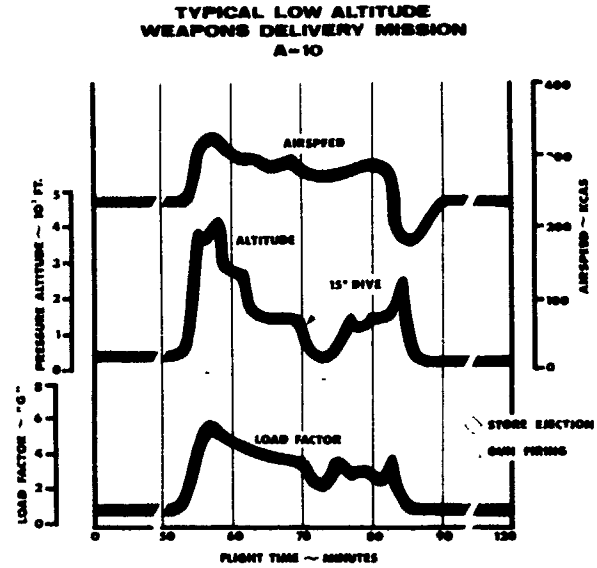

Figure 1

STRESS OF LOW ALTITUDE HIGH SPEED FLIGHT

PHYSICAL	PSYCHOLOGICAL
VIBRATION	TASK OVERLOAD
NOISE	SURVIVAL
HEAT	FATIGUE
VISIBILITY	SYSTEMS CONFIDENCE
MOTION SICKNESS	DISORIENTATION

Table I

STRESSORS ON B-52 CREWMEMBERS

VIBRATION

GUSTS

HEAT

MOTION SICKNESS

SURVIVAL

NOISE

EMERGENCY ESCAPE

Table II

STRESSORS ON THE FB-111 CREW

- VIBRATION
- VISIBILITY
- TASK LOAD
- DISORIENTATION
- BIRDSTRIKES
- COCKPIT DISTRACTIONS

Table III

STRESSORS ON THE A-10 PILOT

TASK LOAD

FATIGUE

'G FORCES

HEAD UP EYES OUT

VISIBILITY

SURVIVAL

Table IV

CONTRIBUTIONS MADE AND TO BE MADE BY BIOTECHNOLOGY IN SUPPORT OF LAHS FLIGHT

VIBRATION
NOISE
G PROTECTION
ESCAPE SYSTEMS
VISUAL DISPLAYS
AURAL INFORMATION
COCKPIT CONTACT
TASK LOADING
AUTOMATED SYSTEMS
HUMAN ENGINEERING

Table V

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PROBLEMES THERMIQUES POSES PAR LE VOL A GRANDE VITESSE ET A BASSE ALTITUDE

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RESUME

Le vol a basse altitude grande vitesse est susceptible de créer dans certains cas pour les pilotes des conditions dépassant les limites de tolérance. Les facteurs physiques de l'environnement ont fait l'objet de nombreuses études ainsi que leurs conséquences sur les performances. Une prévision du temps de tolérance à partir du stockage de chaleur est présentée et discutée. Elle met en évidence le rôle important joué par l'hygrométrie de l'air et l'activité physique du pilote. La prévention de ces inconvénients climatiques nécessite l'utilisation de moyens relativement simples à mettre en oeuvre avant le vol. En cours de vol elle implique d'avoir été prévue lors de la conception des avions.

Le vol à grande vitesse et basse altitude soumet le pilote à de nombreuses contraintes, entre autres dans certains cas à une contrainte thermique plus ou moins importante. Ceci tient au fait que les systèmes de climatisation des avions, satisfaisant en altitude, ne le sont plus au voisinage du sol, quand la température et l'hygrométrie de l'air sont élevées. Dans ces conditions, on court le risque de voir apparaître une détérioration des capacités psycho-sensori-motrices des pilotes, ce qui est particulièrement préjudiciable dans ce type de vol. L'estimation de ce risque et sa prévention ont fait l'objet de très nombreux travaux d'un point de vue général. Les données spécifiques aux avions de combat sont beaucoup plus restreintes. Quoiqu'il en soit, il est actuellement possible de se faire une idée relativement précise de ce facteur de risque. Les notions sur ce problème sont regroupées sous 3 rubriques principales :
- évaluation de l'ambiance thermique
- évaluation de la tolérance humaine
- amélioration de la tolérance.

Un développement original sera consacré à la prévision de la tolérance à partir du stockage thermique.

1. EVALUATION DE L'AMBIANCE THERMIQUE.

La contrainte thermique revêt de multiples causes :
- avion surchauffé par un long séjour sur un parking ensoleillé,
- air chaud et humide en basse altitude,
- rayonnement solaire et effet de serre du cockpit,
- échauffement aérodynamique qui commence à faire sentir ses effets pour des vitesses voisines du mach,
- échauffement par électronique de bord d'autant plus important que les aides à la navigation sont développées,
- production calorique du pilote qui est plus élevée que dans la plupart des autres conditions de vol en raison de la difficulté du pilotage et des contraintes particulières à cette situation,
- port d'équipements gênant pour la thermolyse tels que vêtements anti-G, anfi-flack, anti-immersion, de protection contre les gaz de combat etc.....

1-1 L'attente au sol, généralement en conditions d'alerte doit être prise en considération, car elle fixe les conditions thermiques initiales. Ainsi HOUDAS et COLIN (1) ont observé pour des températures ambiantes moyennement chaudes (Ta = 25,2°C), mais avec rayonnement solaire intense, une température à l'intérieur du cockpit très élevée, la température sèche atteignant 32,6° C et la température globe 50°C. Par temps très chaud (Ta = 37,5°C), et fort ensoleillement, la température sèche dans le cockpit était de 50°C et la température globe de 60°C.

De la même façon, NUNNELEY et MYRHE (2) observent, dans certaines conditions, au bout d'une heure d'attente au sol en plein soleil, une température sèche supérieure à 50°C et une température globe supérieure à 65°C, ce qui, compte tenu de l'humidité, permet de calculer un index WBGT supérieur à 36°C.

1-2 Un certain nombre de données ont permis d'apprécier les conditions climatiques en vol. Ainsi, dans un travail antérieur (3), l'évaluation de la charge thermique par rayonnement avait été tentée à bord d'un avion MIRAGE III B à l'aide d'un "Steradiometer". Cet appareil constitué d'une sphère pourvue de 34 capteurs (disques de platine noircis, à la face postérieure desquels se trouvent les thermocouples placés en série), réalise un modèle étalonné de façon à indiquer ce que reçoit un homme par m2 de surface corporelle lorsque cette surface est à 32°C. Des mesures effectuées du sol jusqu'à 50 000 pieds, seules ont été retenues celles effectuées au sol (250 pieds) à 10 000 pieds et à titre de comparaison au-dessus de 40 000 pieds. Les essais ont été réalisés 3 jours consécutifs les 6, 7 et 8 septembre, l'avion faisant un circuit de 360 degrés afin de recevoir le soleil successivement sous tous les angles. Les résultats sont présentés sur la figure 1. Ils montrent que la charge thermique radiante se situe, dans la zone qui nous interesse, c'est-à-dire du sol à 10 000

pieds, entre 100 à 200 Watts/m2 en moyenne. Il existe une certaine hétérogénéité liée à l'asymétrie de la position du capteur à l'intérieur de la cabine. On peut supposer qu'à d'autres périodes de l'année (juin, juillet, août), au milieu de la journée et par ciel clair, ces valeurs seraient plus élevées.

La surface corporelle exposée au rayonnement solaire est relativement modeste, mais dans tous les cas la tête est concernée, ce qui est un facteur défavorable pour la tolérance. La mise au point de systèmes de mesure miniaturisés (4) (5) a permis de multiplier aisément les enregistrements à bord des aéronefs, de la température sèche, la température globe, l'humidité, la vitesse de déplacement de l'air et la pression barométrique.

ALLAN et COLL (6) dans des vols à basse altitude, par des températures extérieures peu élevées ont montré les relations entre la température de l'air et les conditions climatiques à l'intérieur du cockpit. A cette occasion, ils estiment que tant que la température extérieure ne dépasse pas 25°C on reste dans la zone "prescriptive" de Lind, c'est-à-dire celle où la thermorégulation ne pose pas de problèmes particuliers.

Cet ensemble de données , a été à l'origine de comparaisons entre les conditions ambiantes et celles règnant à l'intérieur des aéronefs. A l'aide des résultats de HARRISON et Coll (7) et moyennant certaines approximations, STRIBLEY et NUNNELEY (8) établissent un index de contrainte thermique sur avion de combat (F.I.T.S. : Fighter Index of Thermal Stress) qui est l'équivalent de l'index WBGT dans le cockpit. L'intérêt du F.I.T.S. est qu'il nécessite seulement deux mesures à l'extérieur, les températures sèche (T_{db}) et humide (T_{wb}) au lieu des trois mesures utilisées pour le WBGT, température globe, sèche et humide, ces dernières devant être effectuées dans le cockpit. L'équation permettant le calcul de ce nouvel index est la suivante :

$$F.I.T.S. = 0.8281\ T_{wb} + 0,3549\ T_{db} + A \qquad (1)$$

Le terme A permet une correction en fonction de l'ensoleillement. Il est de 5,08°C au soleil et 2,23°C par temps moyennement couvert.

Cette approche , malgré certaines approximations, représente donc un moyen particulièrement simple de prévision des conditions climatiques dans la cabine.

2. TOLERANCE HUMAINE.

Il s'agit d'un problème très pratique qui a suscité de très nombreux travaux. La tolérance peut être évaluée soit d'après des critères thermiques physiologiques, soit d'après les caractéristiques de l'ambiance.

2-1 Les critères physiologiques n'ont pas tous la même valeur dans le cas du pilotage d'un aéronef. Ainsi, en ce qui concerne la Température rectale, il a été montré que l'homme pouvait continuer à être actif pendant un temps limité à 39°C. Par contre, les performances psycho-sensorielles sont diminuées avant ce seuil. La tolérance aux autres facteurs agressifs du vol tels que les accélérations est également diminuée bien avant (9). En fait, compte tenu de la durée relativement brève de la plupart des vols basse altitude et compte tenu de la lenteur de l'évolution de la température rectale, ce paramètre ne nous semble pas être un bon critère. La Température cutanée est beaucoup plus sensible, et constitue un excellent index pour apprécier le confort, celui-ci étant obtenu lorsque la température cutanée moyenne (T_{sk}) est de 34° ± 1°C, avec une répartition homogène sur la surface du corps. Concernant la tolérance proprement dite, IAMPIETRO (10) considère que celle-ci est de deux heures lorsque $\bar{T}_{sk}$ est de 37°C. Mais là aussi il est vraisemblable que cette température cutanée correspond à un état thermique du corps compatible avec le maintien des performances du pilote. De plus notamment en cas d'ensoleillement intense, il existe une certaine hétérogénéité avec des températures élevées au niveau de la tête et de la poitrine (2,11). Les conséquences de ce phénomène, très défavorables sur le plan du confort, sont difficiles à apprécier sur le plan de la performance.

Le stockage de la chaleur est un autre critère interessant mais dont la détermination se heurte à certains problèmes. Une approche théorique du temps de tolérance peut être tentée. Si QS est le stockage de chaleur accumulée dans le corps et représente une limite qui ne doit pas être dépassé et S le stockage par unité de temps, la durée pour atteindre cette valeur limite de QS sera :

$$t = \frac{QS}{S} \qquad (2)$$

On connaît par ailleurs l'équation du bilan thermique :

$$S = M \pm R \pm C \pm K - E \qquad (3)$$

où M est la production de chaleur métabolique, R, C, K, sont les échanges de chaleur par radiation, convection, conduction et E les pertes de chaleur par évaporation, le tout exprimé en débit calorique (kcal/(m2.h) ou W/m2).

La détermination de chacun de ces termes doit permettre d'établir le temps de tolérance. Mais cette détermination est très difficile et d'un point de vue pratique certaines approximations sont nécessaires dans un but prévisionnel. On peut en première approximation négliger les transferts par conduction. L'évaluation de l'évaporation pose par contre un problème très ardu, car elle ne peut être assimilée à la perte de poids sudorale. Les équipements, le contact du siège limitent en effet considérablement les possibilités évaporatoires. De plus, lors d'un vol à basse altitude dans des pays tropicaux ou au-dessus de la mer, l'hygrométrie à l'extérieur aussi bien qu'à l'intérieur du cockpit peut être plus élevée. On peut considérer deux cas extrêmes. Celui où l'air étant saturé d'humidité, aucune évaporation n'est possible dans la gamme des températures qui nous interessent (E = 0), et celui où l'évaporation se fait dans les meilleures conditions. Dans ce second cas, il faut considérer qu'inévitablement une partie importante de la surface du corps n'est le siège d'aucune ou de très peu d'évaporation. Il s'agit des membres inférieurs et de l'abdomen du fait des équipements, notamment l'anti G, du dos en raison du contact avec le siège et de la tête à cause du port du casque et du masque. Cette surface exclue des processus évaporatoires peut être évalué à environ 60 %, de la surface corporelle. Ainsi pour un homme de taille moyenne (surface corporelle = 1,90 m2) avec un débit sudoral très important (800g/h), le refroidissement évaporatoire dans les meilleures conditions sera relativement faible, de l'ordre de 100 kcal/(m2.h), (E = 100).

L'activité métabolique peut aussi varier dans d'assez larges proportions. A priori on peut considérer que la dépense énergétique doit le plus souvent se situer entre 100 kcal/(m2.h), (M = 100) et 150 kcal/(m2.h), (M = 150).

Les échanges caloriques par radiation et convection peuvent être estimés approximativement en considérant que la température cutanée moyenne pour un sujet exposé à la chaleur est de 36°C et que le coefficient combiné d'échange par radiation et convection (12, 13) est de 8 kcal/(m2.h). Si par simplification nous considérons que la température de l'air est égale à la température radiante il vient : R + C = 8 (Tg - 36), où Tg est la température globe.

Concernant l'accumulation de chaleur dans le corps (QS), BLOCKELEY et Coll (14) considèrent que les performances sont intactes à 40 kcal/(m2) et que la limite à ne pas dépasser est de l'ordre de 54 kcal/m2. En prenant une valeur de 50 kcal/m2 le temps de tolérance en minutes (t) peut ainsi être prévu par la relation :

$$t = \frac{(50 \times 60)}{M + 8\,(Tg - 36) - E} \qquad (4)$$

La figure 2 représente les temps de tolérance calculés d'après cette équation dans 4 situations différentes selon que le métabolisme est de 100 ou 150 kcal/(m2.h) et l'évaporation de 0 ou 100 kcal/(m2.h).

Pratiquement lorsque l'évaporation peut se faire dans de bonnes conditions, on voit que pour un vol de 1 heure la température globe à ne pas dépasser va de 36°C à 42°C selon l'activité du pilote. Cet écart est important. Il met l'accent sur le rôle du facteur métabolique souvent négligé. Ce type de vol à basse altitude peut en effet par fortes turbulences exiger une dépense énergétique très au-dessus de celle habituellement rencontrée en vol normal, et ceci aura des conséquences notables sur la tolérance.

En atmosphère saturée d'humidité le temps de tolérance chute très vite. Toujours pour 1 heure de vol, il faut retenir une température globe limite de 24,5° à 30°C selon l'activité. En fait ces chiffres sont surement un peu trop bas car en dessous de 36°C, en ambiance saturée une certaine quantité de sueur peut s'évaporer, bien que son estimation correcte ne soit pas possible. Elle ne peut donc pas être prise en compte.

2-2 La détermination de la tolérance sur des critères thermiques physiologiques n'étant pas pratique au point de vue opérationnel, de nombreuses tentatives de prévision ont été faites à partir des caractéristiques de l'ambiance. Toutefois, l'application des données sur la question au cas spécifique d'un avion de combat reste délicate. L'une des difficultés rencontrées tient au choix des paramètres destinés à caractériser l'ambiance. Parmi les nombreux index proposés, l'un des plus utilisés est la Température effective (Te) qui est fonction de la température et de la vitesse de l'air ainsi que de son hygrométrie.

Une revue de la littérature (15), a montré quelle était la limite moyenne du maintien des performances en fonction de la température effective et du temps (figure 3). Dans l'ensemble, pour des temps inférieurs à 90 minutes, il existe des variations assez importantes des Te tolérées. Ainsi, à partir de 90 minutes et au-delà, la limite de température effective se situe vers 29°C. Pour un vol de 60 minutes, elle est de 30°C et, pour 45 minutes de 31,5°C. Pour une heure, cela correspond schématiquement à des températures d'air calme allant de 30°C avec 100 % d'humidité relative à 45°C avec 18 % d'humidité relative.

Ces conclusions sont en accord avec celles de GRETHER (16) qui considère, d'après une approche quelque peu différente, que la limite du maintien des performances, sans toutefois préciser le temps correspond à une température effective de 29,5°C.

L'index WBGT a également été discuté (8, 17) et la limite de sécurité proposée pour un pilote est de 32°C. C'est également ce qui a été retenu pour le F.I.T.S. avec en plus une limite dangereuse à franchir, fixée à 38°C. Cette limite parait légèrement au-dessus de celle donnée par la température effective : Une température effective de 30°C correspond en effet à peu près à un index WBGT de 30,5 à 31,5°C.

Exprimée différemment en considérant la température de l'air à l'extérieur du cockpit, la limite de sécurité correspond, d'après les tables de STRIBLEY et NUNNELEY (8), a des ambiances extérieures à l'avion allant de 35°C en atmosphère sèche à 22,5°C saturé en plein soleil, ou de 40°C en air sec à 25°C saturé pour un ensoleillement modéré.

3. AMELIORATION DE LA TOLERANCE.

Un certain nombre de mesures doivent permettre d'améliorer la tolérance lors des vols basse altitude grande vitesse

3-1 Au niveau individuel un certain nombre de règles d'hygiène doivent être inculquées au personnel. Celui-ci devra en effet veiller à se maintenir dans les meilleures conditions physiques et pour cela éviter toute fatigue inutile notamment avant les vols. Son régime alimentaire et hydrosodé sera particulièrement surveillé. On insistera sur l'importance de ces précautions pendant les 15 premiers jours du séjour dans un climat tropical, où l'organisme ne s'est pas encore adapté aux nouvelles conditions. Dans toute la mesure du possible, des locaux climatisés devront être mis à la disposition des équipages.

3-2 Au plan opérationnel proprement dit, il parait essentiel que, au moment du décollage, les pilotes soient dans un état confortable. Le temps de tolérance à la chaleur vis à vis de contraintes que l'on peut considérer comme aiguës, dépend en effet étroitement des conditions physiologiques initiales. Il sera en effet bien plus court si les équipages ont déjà accumulé de la chaleur dans leur organisme avant le début de la mission. Les moyens pour obtenir un tel résultat sont connus

- salle d'opération bien climatisée avec des boissons fraiches non alcoolisées.
- protection des aéronefs, en stationnement sur le parking, vis à vis du rayonnement solaire par un système parasoleil.
- ventilation des cabines au sol par un groupe de conditionnement suffisamment puissant pour éliminer la chaleur due aux conditions climatiques locales et éventuellement si l'avion est en alerte, celle dégagée par l'électronique de bord.

De tels dispositifs ont fait la preuve de leur efficacité depuis longtemps (18). Par l'association d'un groupe de climatisation fournissant de l'air à 22°C avec un débit de 3 0001/min. et d'un parasol, il a été possible de ramener la température globe de 53°C à 33,2°C avec une température sèche de 22,6°C. Un tel système permet une attente en alerte, le pilote étant à l'intérieur de son appareil sans problème particulier. Dans l'expérience ci-dessus, la température cutanée moyenne s'est stabilisée à 33,9°C ce qui est tout à fait compatible avec le confort.

3-3 En cours de vol, si les conditions climatiques et opérationnelles, sont telles que les précautions précédentes s'évèrent insuffisantes, d'autres mesures telles que l'amélioration de la climatisation de la cabine et l'utilisation d'équipements individuels ventilés pourront être envisagés.

Les possibilités des systèmes de climatisation de la plupart des avions en service sont insuffisantes pour assurer le confort du pilote au cours des vols basse altitude dans des conditions climatiques extrêmes. Leur amélioration souhaitable du point de vue médical, se heurte à des problèmes techniques complexes et onéreux difficiles à résoudre.

La climatisation individuelle par combinaison ventilée est une solution plus simple. De nombreuses réalisations de ce type d'équipements ont prouvé son efficacité. Ainsi le vêtement français EFA 25 permet de maintenir un pilote dans des conditions confortables malgré une température ambiante de 60°C (19). Des groupes de ventilation au sol permettent d'assurer le confort du pilote porteur de vêtements spéciaux (pressurisés, anti-immersion etc...) pendant l'alerte en salle.

De plus l'utilisation d'un groupe de ventilation portable de la taille d'une petite valise, permet d'assurer son confort lors des déplacements sur le parking et éventuellement lors de l'attente en alerte à l'intérieur de l'appareil, s'il n'existe pas de groupe d'alerte (20). En vol, un dispositif permettant l'insufflation d'air dans le vêtement est nécessaire mais ceci suppose la mise en place de l'appareillage adéquat à l'intérieur de l'avion et par conséquent de le prévoir dès sa conception.

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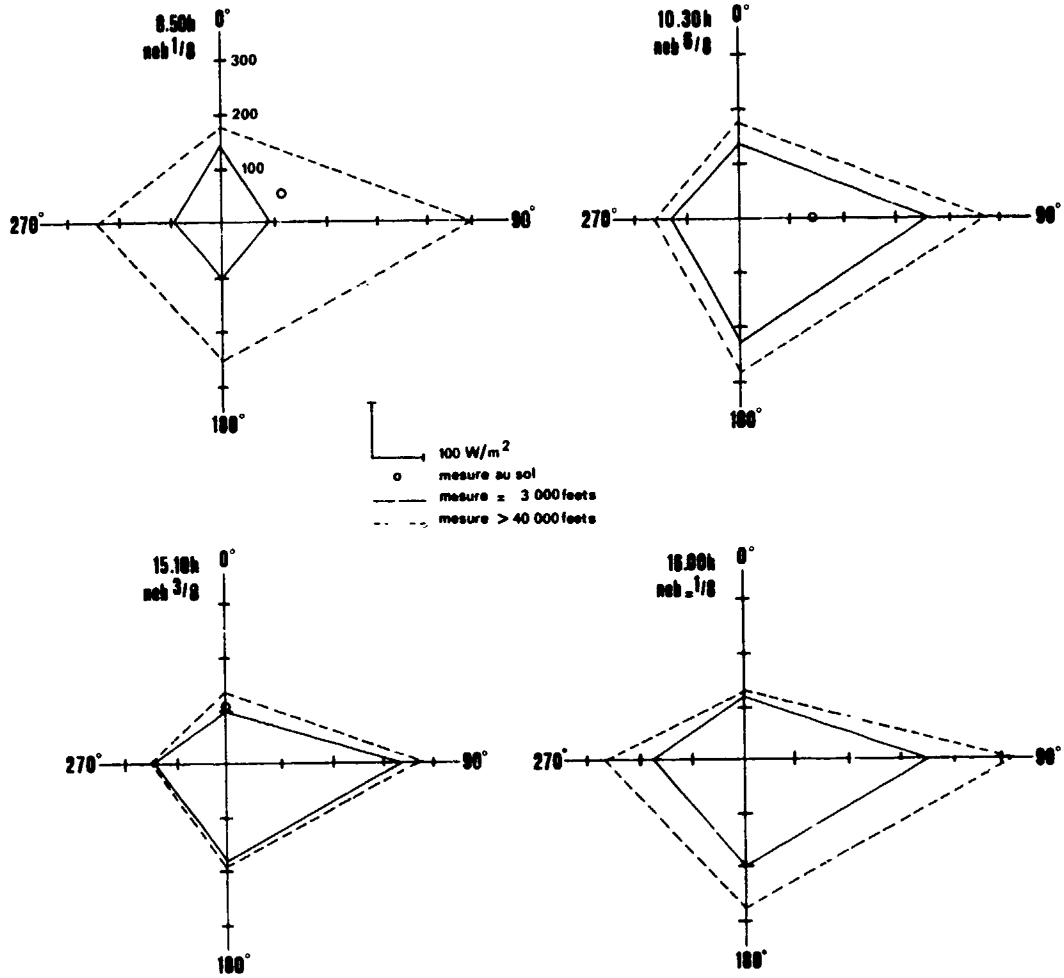


FIGURE 1.

Charge radiante à l'intérieur d'un MIRAGE III B mesurée au Stéradiometer au sol (O), à 3 000 pieds (_____) au-dessus de 40 000 pieds (-------), les 6, 7 et 8 septembre, avec au sol T air = 24/25°C, Humidité relative = 50/65 %.
V = 0,8 à 0,9 mach au sol et 3 000 pieds, 1 à 1,2 à haute altitude couches nuageuses en dessous de 3 000 pieds.

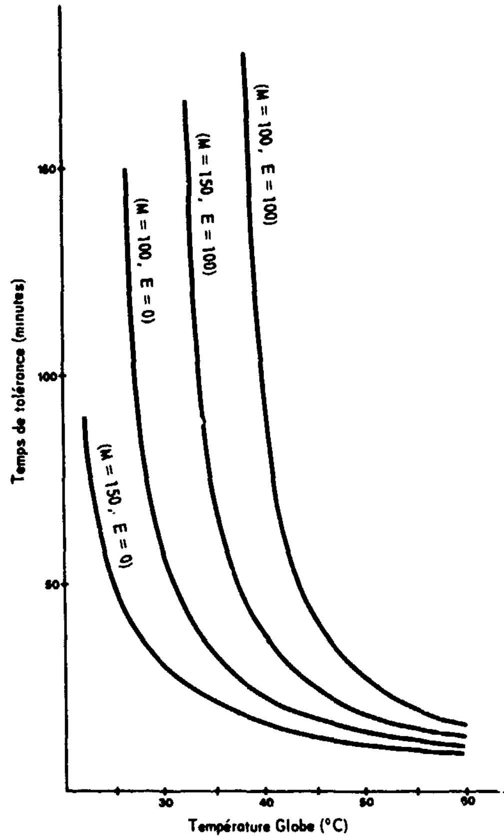


FIGURE 2.

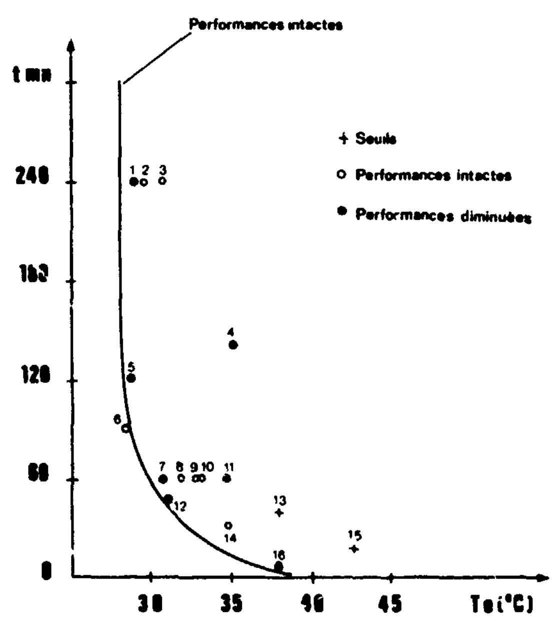
Temps de tolérance en fonction de la température globe dans le cas ou la température de l'air est identique à la température radiante.

Quatre situations sont représentées selon l'activité du pilote (M = 100 ou 150 kcal/(m2.h) et les possibilités évaporatoires (nulle avec E = 0 et très importante avec E = 200 kcal/(m2.h).
(Cf. texte)

FIGURE 3.

Temps de tolérance (t) en minutes en fonction de la température effective (Te). Les données sont celles de :
(1) Viteles et Smith 1946
(2) Reilly et Parker 1967
(3) Loeb et Coll 1956
(4) Bursill 1954
(5) Moreland et Barnes 1969
(5) Pepler 1963
(6)(7) Colin et Coll 1973
(8)(11) Wing et Touchstone 1963
(9) Chiles 1958
(10) Carlson 1961
(12) Brivel 1971
(13)(15) Blockley et Lyman 1950, 1951
(14)(16) Iampietro et Coll 1969.

Le détail de ces références se trouve dans la référence 15 du présent article.



EFFECTS ON PERFORMANCE OF THERMAL STRAIN ENCOUNTERED DURING HIGH SPEED, LOW-LEVEL FLIGHT

by

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SUMMARY

Performance decrements in simulated flight have previously been demonstrated at levels of thermal stress equivalent to those found in the cockpits of high performance aircraft. However, the levels of body temperature at which these performance decrements occur are uncertain. Previous studies have shown that performance of a simple, motor task may be degraded by heating the skin when the body temperature is above a critical level of 37.6°C. The experiment reported here confirms these findings for performance in a simple flight simulator. The operational significance of the results is discussed.

INTRODUCTION

Recent advances in technology (e.g. 1) have allowed collections of aircrew and cockpit thermal data to be made during routine, high speed, low level flight in various military aircraft. Typical results are given in Table 1. The highest cockpit temperatures were measured when the aircraft was on the ground. In addition, Belyavin et al (7) predict from laboratory experiments that aircrew flying in NBC clothing in Germany in summer could reach a deep body temperature of 37.9°C in 41 min and 38.5°C in 72 min.

Table 1. Maximum Aircrew and Cockpit Temperatures Recorded in Various Aircraft[1]

Aircraft	Deep Body Temperature		Skin Temperature		Cockpit Temperature	Reference	Notes
	°C	Site	°C	Site	WBGT °C		
Harrier	38.0	ac[2]	37.4	mean	31	2	
Buccaneer	38 2	ac	36.3	mean	25	2	
Phantom	37.8	ac	36.6	mean	-	2	
Gazelle	37.6	ac	37.1	mean	26	2	
Scout	-	-	37.0	mean	23	2	
Jaguar	38.0	ac	37.2	mean	36	3	Failed cabin conditioning
Mohawk	38.0	re[3]	37.2	xiphoid	30	4	
F15	37.5	re	38.9	arm	36.4	5	Aircraft on ground in sun
F111A	-	-	38.9	mean	-	6	
F4E	38.1	ac	36.6	mean	37.8	Allan (unpublished observations)	Aircrew wearing NBC protective clothing

Notes

1. The three temperatures for each aircraft were not necessarily recorded on the same occasion.
2. ac - auditory canal.
3. re - rectal.

Recent work at this Institute (8,9,10) showed that performance of a pursuit rotor task was unaffected by heating or cooling until deep body temperature exceeded 37.6°C but that above this performance was worse during heating than cooling (Fig.1). Above the critical level of core temperature, the skin temperature was found to be a more important determinant of performance than deep body temperature, although it was impossible to discount the possible effects of direction and rate of change of deep body and skin temperatures. It was suggested that absolute levels and rates of change of core and skin temperatures influenced performance together through their effect on affective thermal sensation and there appeared to be a critical level of discomfort beyond which decrements of performance developed.

The aim of the experiment reported here was to extend this work to a task more representative of flying, while still using levels of core and skin temperature similar to those measured in or predicted for aircrew.

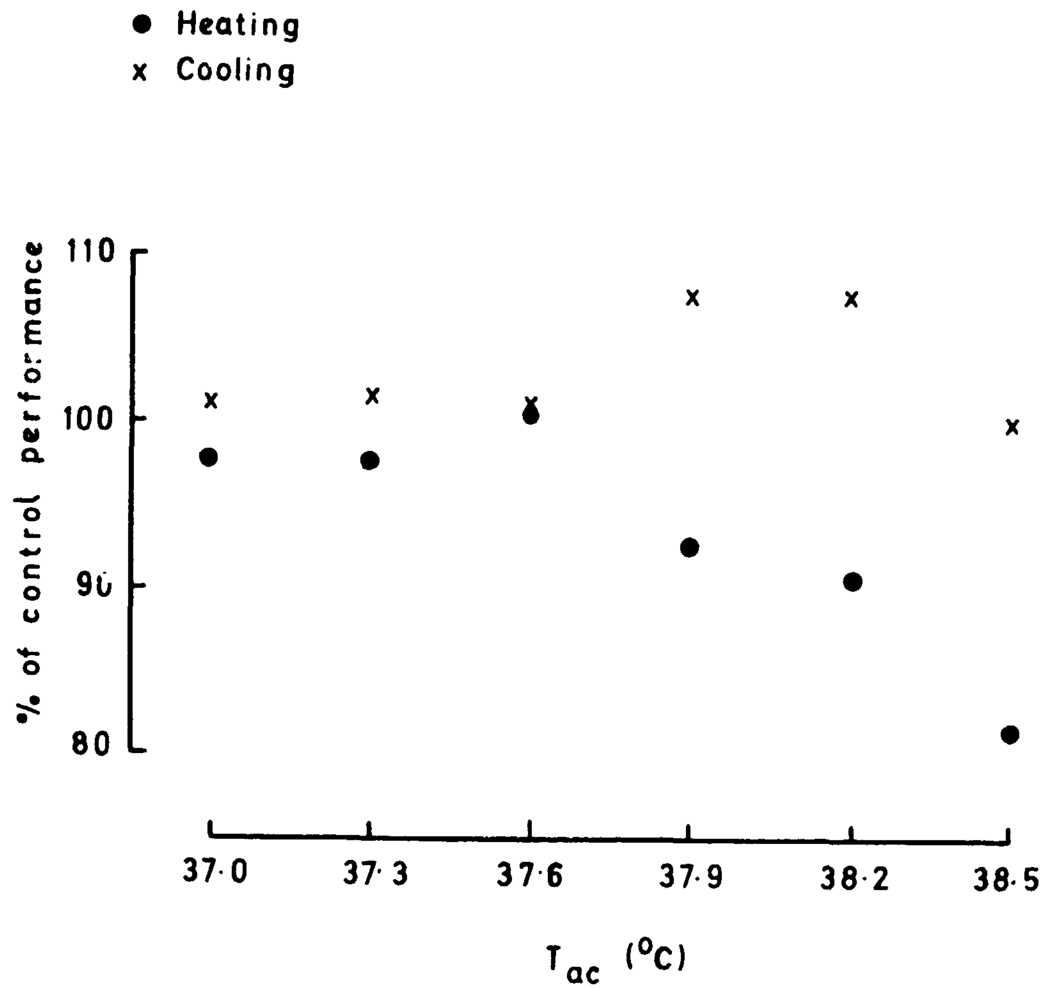


Figure 1. The relationship between rotary pursuit task performance and deep body temperature (T_{ac}).

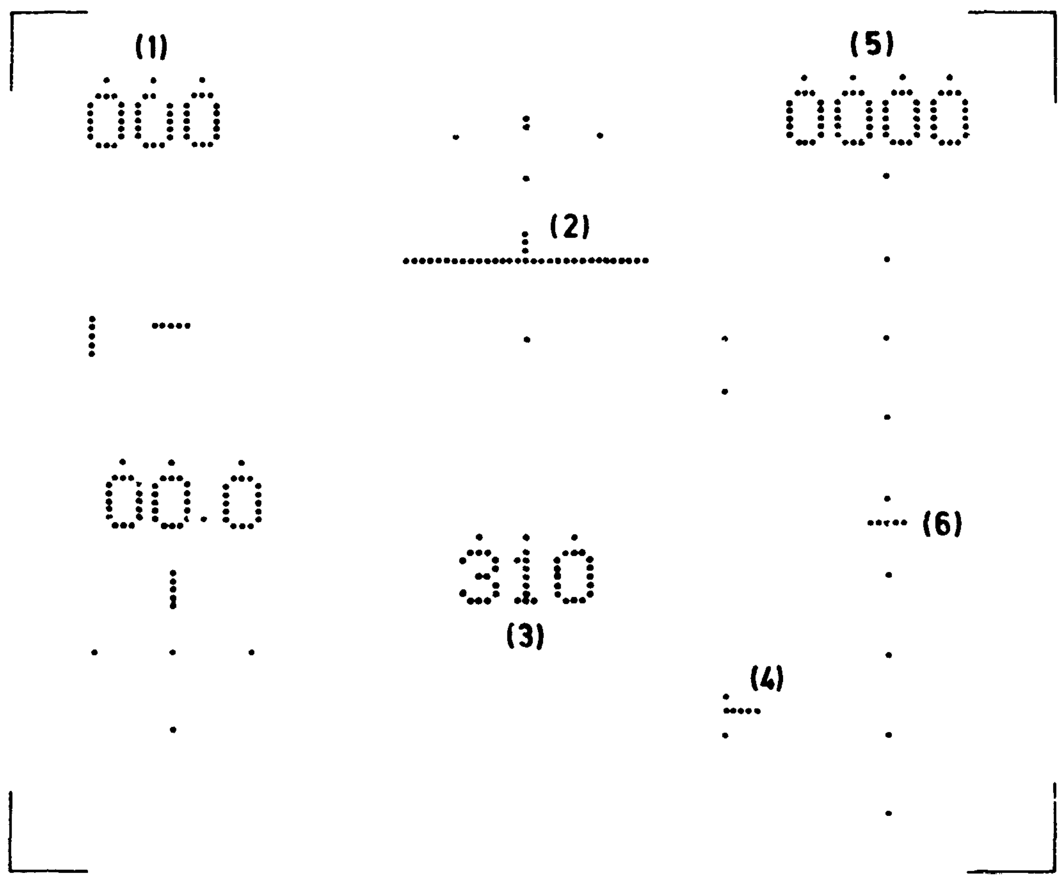
METHODS

Nine male volunteers, aged between 19 and 41 years, acted as subjects. Six had previously been exposed to hot conditions although none was acclimatized to heat. Each subject carried out two replicate experiments in which he was first heated to a deep body temperature (T_{ac}) of 37.5°C, then alternately heated and cooled twice between T_{ac} limits of 37.9 and 38.5°C, and finally cooled to a T_{ac} of 37.5°C (see Fig.3). Heating or cooling was achieved by controlling the inlet temperature of a liquid conditioned suit (LCS) at either 50°C or 28°C.

Measurements. Core temperature was measured from the auditory canal using a thermistor near to, but not touching, the eardrum, and well insulated from the environment using cotton wool and a cloth flying helmet. Thermistors were also used to measure the skin temperature at 4 sites (lateral upper arm, chest, thigh and calf); mean skin temperature ($\bar{T}_{sk}$) was taken as the arithmetic mean of the four measurements. Core and skin temperatures were measured at ½ min intervals using a data logger. A subjective assessment of thermal comfort was obtained by the 10 cm line technique (11) with the line annotated 'thermally ideal' at one end and 'thermally intolerable' at the other.

The Task. The subject had to 'fly' a simplified form of flight simulator (12) while controlling certain flight vectors within defined limits by use of throttle and control column. The simulator had no rudder controls. Performance and handling was considered to be equivalent to that of a small business jet, e.g. the HS 125. The visual display, on a television screen (Fig.2), consisted of digital outputs from an air speed indicator, an altimeter and a compass, with analogue presentations of vertical speed, power setting and artificial horizon. Three navigational aids were also displayed but were not used in the present experiment. A printed card, placed below the television screen, gave the subject the required altitudes and headings for the task period.

Means and variances of samples taken three times a second were obtained, through a DEC PDP-12 computer, of the following variables for each manoeuvre:



(1) Airspeed indicator
(2) Artificial horizon and Turn/Bank indicator
(3) Compass
(4) Power setting
(5) Altimeter
(6) Vertical speed indicator

Figure 2. The television display of the flight simulator.

a. Heading (HDG).
b. Altitude (ALT).
c. Air Speed (IAS).
d. Vertical Speed (VS).
e. Bank angle (BA).

In addition, data was obtained for the number of times in each manoeuvre the major controls passed through the neutral position (aileron and elevator reversals) as well as for the average maximum extent of the control column movements.

Each 3 min task period comprised:

a. An ascending turn from 3,500 ft to 5,000 ft through 150° from a previously set heading (which varied with each task period). Vertical speed had to be maintained at +2,500 ± 200 ft min^{-1} with an angle of bank of 30 ± 2½°.

b. Straight and level flight with random sine wave turbulence (12) at ALT 5,000 ± 50 ft, at ±5° from the required heading, at VS 0 ± 50 ft min^{-1} and at BA 0 ± 2½°.

c. A descending turn from 5,000 ft to 3,500 ft through 150°. Vertical speed had to be -2,500 ± 500 ft min^{-1} with an angle of bank of 30 ± 2½°.

Indicated air speed during the three manoeuvres had to be maintained at 210 ± 20 knots. The three parts of the task were separated by periods of up to 20 sec to allow the subject to correct height and heading between the measured parts of the task.

Each subject was given a minimum of six, 45 min lessons on the simulator, of which the first four were general instruction, flight theory and control of the simulator, and the remainder were devoted to flying the specific manoeuvres. The subject had a further practice within 24 hr of his experimental runs; in addition, he received a further practice session if more than 3 days separated experiments.

Procedure. After being instrumented for measurement of core and skin temperature, the subject dressed in the LCS, long-limbed acrilan pile underwear, socks, cold weather flying jacket and trousers, boots, gloves and cloth flying helmet. He then entered the climatic chamber, which was maintained at 30°C, and carried out a 3 min practice task. The subject then mounted a bicycle ergometer and started exercise at 100W while heating was started through the suit conditioning unit. He stopped exercise at a T_{ac} of 37.3°C and transferred to the seat of the flight simulator. The task was performed at T_{ac} 37.5°C, and then at 3 levels of T_{ac} (37.9, 38.2 and 38.5°C) during each heating and cooling phase, and finally was performed at 37.5°C again during the final cooling phase (see Fig·3). The task was timed so that its midpoint coincided with the target T_{ac}. Immediately after each task, a subjective assessment of thermal comfort was obtained from the subject.

RESULTS

The results for T_{ac} and $\bar{T}_{sk}$ at the midpoint of each task, averaged for subjects and replicates, are shown in Table 2 and Fig·3. It can be seen that the intended levels of T_{ac} during performance of the task have been accurately achieved. Despite a constant inlet temperature to the LCS, $\bar{T}_{sk}$ continued to rise slightly during heating and to fall during cooling but the differences were small when compared to the differences between average levels for heating (39.0°C) and cooling (36.4°C). Also shown in Table 2 and Fig·3 are the average values for subjective level of thermal comfort immediately after each task.

Table 2. Means and SD (subjects/replicates) for T_{ac}, $\bar{T}_{sk}$ and subjective level of thermal comfort at each task performance during heating and cooling

PHASE	HEATING				COOLING			HEATING			COOLING			
TASK	1	2	3	4	5	6	7	8	9	10	11	12	13	14
T_{ac} °C	37.53	37.88	38.19	38.49	38.53	38.20	37.91	37.93	38.26	38.54	38.53	38.21	37.94	37.52
SD	0.05	0.03	0.03	0.02	0.05	0.04	0.04	0.02	0.04	0.03	0.03	0.03	0.03	0.04
$\bar{T}_{sk}$ °C	38.4	38.7	39.0	39.1	36.8	36.4	36.2	38.9	39.0	39.0	36.5	36.3	36.0	34.7
SD	0.5	0.4	0.4	0.4	0.3	0.3	0.3	0.4	0.5	0.5	0.4	0.3	0.4	0.5
Comfort cm	3.7	5.3	6.2	6.8	2.6	1.4	1.3	5.7	6.5	7.0	2.0	1.4	1.0	0.6
SD	2.0	2.3	2.3	2.5	1.6	0.9	1.0	2.7	2.8	2.5	1.2	0.9	0.7	0.7

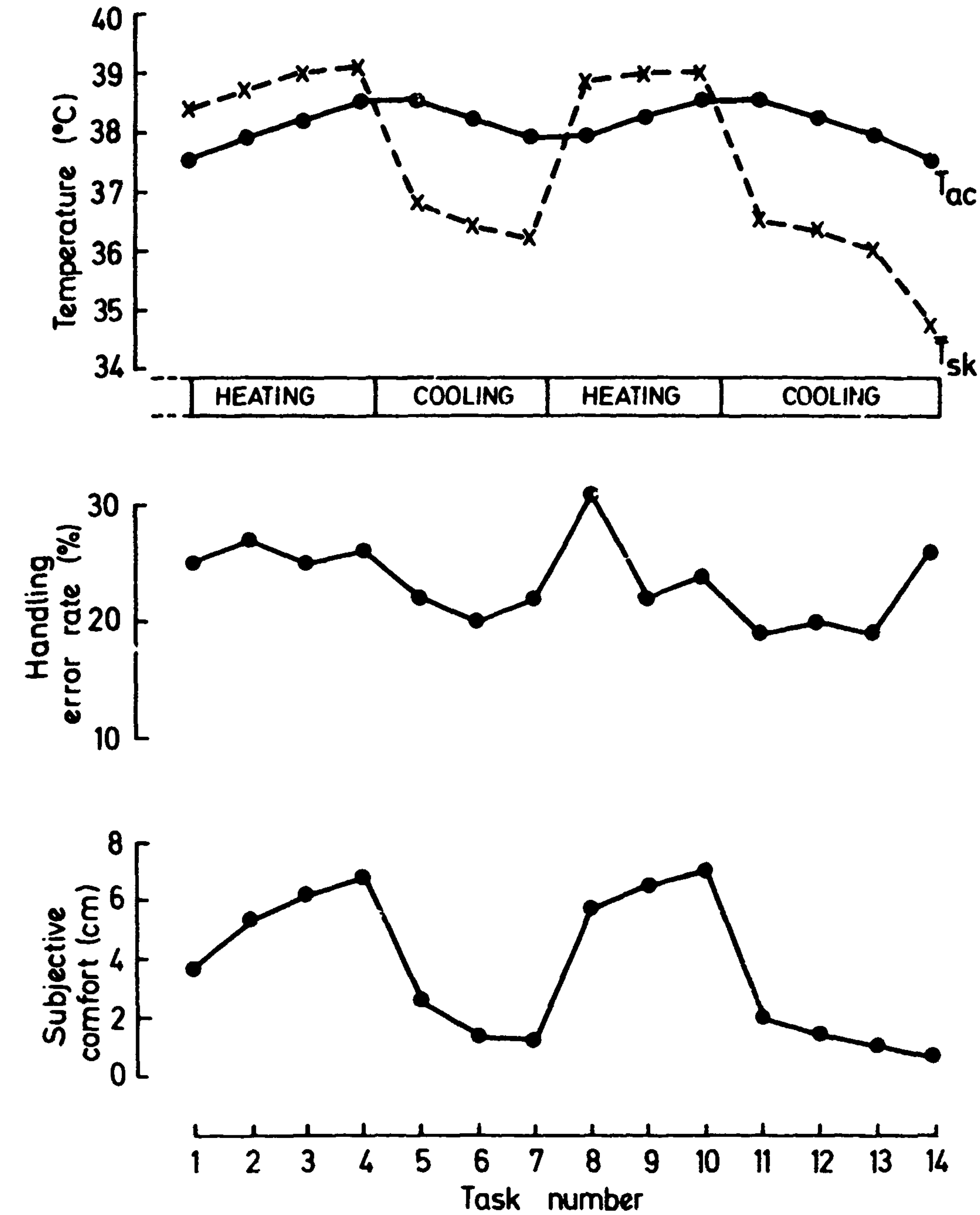


Figure 3. Results showing the relationship of the flight simulator handling error rate and mean subjective thermal comfort to the induced cycles of T_{ac} and $\bar{T}_{sk}$.

The number of occasions that the task mean exceeded the pre-set limit for each flight vector was extracted from the records and each occasion was scored as 1 (error); each time the task mean was within the set limit was scored as 0. The totals for each task period and each manoeuvre are shown in Table 3 and Fig.4. The overall handling error rate is shown in Fig.3. Analysis of variance of the error scores summed over the 11 flight vectors failed to demonstrate any difference between heating and cooling at a core temperature of 37.5°C, but showed a significant decrement during heating compared to cooling at the higher deep body temperatures ($P < 0.02$). There was no demonstrable effect on performance of core temperature between 37.9 and 38.5°C. Apart from the handling errors, subjects also made other errors that were not measurable. These included inability to carry on with the task (on 2 occasions), turning the wrong way (2), ascending instead of descending (1), inability to read the card (2), stopping descending for no apparent reason (2), confusion (1) and losing control (1). All failures, save one instance of stopping descent for no reason, were during a heating phase.

Table 3. Total number of handling errors in each task for each manoeuvre

PHASE	HEATING				COOLING			HEATING			COOLING			
TASK	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Ascending Turn (VS,IAS,BA)	5	5	8	7	8	11	8	13	7	[illegible]	3	3	6	5
Straight/ Level (ALT,HDG,IAS, VS,BA)	27	29	24	25	23	19	20	27	24	26	21	24	17	25
Descending Turn (VS,IAS,BA)	18	19	17	19	12	7	15	20	8	1[illegible]	9	11	10	17

DISCUSSION

The results demonstrate that differences in performance on the flight simulator can be produced by heating or cooling the skin at the same level of deep body temperature. These differences do not exist at a T_{ac} of 37.5°C, but at core temperatures between 37.9 and 38.5°C, performance during heating is worse than during cooling. Above the critical core temperature (i.e. above 37.5°C), skin temperature is a more important determinant of performance than the absolute level of deep body temperature; it is, however, impossible to exclude possible effects on performance of direction and rate of change of both core and skin temperatures. It may be seen from Fig.3 that at a deep body temperature of 37.9°C, heating after cooling may be more stressful than heating alone. In addition, the high error rate during cooling at 37.5°C may reflect the fact that cooling to this level took longer than other parts of the experiment and the greater time gap between tasks could have resulted in the subjects losing concentration. The lack of difference in performance between heating and cooling at a core temperature of 37.5°C could therefore be an artefact but the results compare favourably with the findings in previous studies (9,10).

A loss of accuracy in simulated flying during heat stress has been reported previously. Blockley & Lyman (13) found that subjects in a flight simulator made an increased number of errors when they were reaching their physiological tolerance to environments up to 112°C; the maximum level of rectal temperature (T_{re}) recorded was 39.6°C and the maximum $\bar{T}_{sk}$ was 42.5°C. Moreland & Barnes (14) suggested that pilot performance in a helicopter declined, and variability of performance increased, at higher cockpit temperatures, although the changes reported were not statistically significant. The highest T_{re} that they reported was, however, only 37.7°C. Larsson et al (15) recorded a 25% increase in integrated errors of speed and altitude by subjects flying a Draken simulator at a mean T_{ac} of 38.0°C and $\bar{T}_{sk}$ of 37.5°C compared to flying with T_{ac} 36.8°C and $\bar{T}_{sk}$ 34.0°C. In that experiment, the rate of rise of T_{ac} during the flight phase was very low. Iampietro et al (16) found significant differences in performance in some phases of flight in a simulator between one neutral and two hot environments. Overall, there was a 19% greater deviation from the required heading in an environment of 43°C compared to 23°C, and a further 19% decrement at 60°C compared to 43°C. Mean skin temperature during the hottest flight was 38.5°C although there was little change in T_{re}.

Meister (17) reported similar results for subjects exposed to an environment of 43°C in a flight simulator. A 13% decrement in flying straightforward manoeuvres was observed by the time oesophageal temperature had reached 38.0°C; $\bar{T}_{sk}$ was not reported. Performance in correcting turbulence during straight and level flight was significantly improved by the time of the third heat exposure although this could have been a simple learning effect. When approximately equivalent skin temperatures are compared, the 25% decrement found by Larsson and the 19% decrement found by Iampietro compare favourably with the overall 27% decrement for this study.

In the present experiment, subjects did not only fly less accurately while being heated compared to being cooled, but they also made more drastic errors in controlling the simulator. This type of unpredictable lapse has previously been described (18) for vibration and noise combined and could, if it occurred in real flight, result in the pilot losing control of the aircraft. Bollinger & Carwell (19) state that 'the potential for crew error is increased and ... the margin of safety is, accordingly, decreased during ... hot missions'. Their study was of operational training sorties in the RF4C aircraft in summer (mean maximum temperature 31.6°C) and winter (18.8°C) conditions. They found an increase in the proportion of unsuccessful missions (measured from photo target acquisition scores) attributable to pilot error in summer (24.2%) compared to winter (9.5%). They also commented that the 1.2% dehydration occurring in the 90 min sortie would have caused a 15 to 18% diminution in $+G_z$ tolerance. Elevation of core and skin temperatures can also reduce $+G_z$ tolerance markedly (20).

It is therefore clear that the thermal strain encountered by aircrew in routine high speed, low level flight in warm conditions could cause a reduction in the operational capability of the aircrew. The situation will be exacerbated by anything that increases the thermal strain such as the wearing of more insulative protective clothing, higher work rates (7) and repeated sorties separated by inadequate time for thermal recovery.

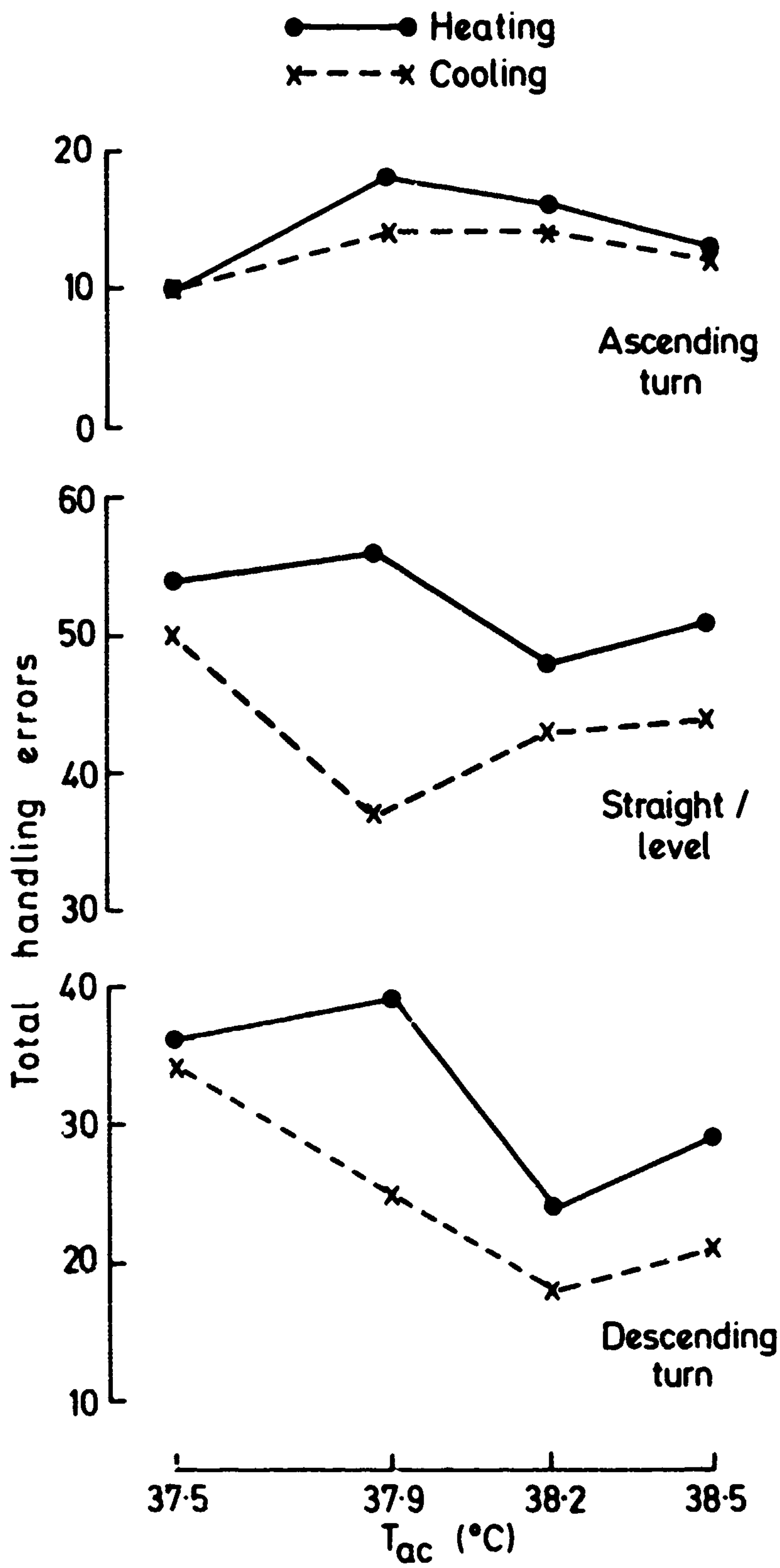


Figure 4. The relationship between T_{ac} and handling errors of the flight simulator in each manoeuvre during heating and cooling.

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DISCUSSION

DR. F.H. AUSTIN (US)

Have you been able to detect a difference in effect of heat and cooling on performance dependent on the birthplace or home (where raised) of aircrew; for example, cold climate versus hot, or wet versus dry climates?

AUTHOR'S REPLY

No. Most of our aircrew were raised in the United Kingdom and, because it is a small country, the climate (cool, temperate) is fairly uniform.

DR. F.H. AUSTIN (US)

Is distraction from the cool or hot air stream a factor in performance decrement in your data?

AUTHOR'S REPLY

Performance seems to be related to thermal comfort - the hotter you feel, the worse you perform. Insofar as this reflects skin temperature, the effect of heating or cooling is to affect performance. However, we used liquid conditioned suits to control heating and cooling in our subjects.

AIRCREW HEAT STRESS DURING HIGH-SPEED, LOW-LEVEL FLIGHT

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SUMMARY

Heat stress is a common problem aboard high-performance aircraft, particularly during high-speed, low-level flight in temperate and hot climates. The degree of heat strain induced in aircrewmembers reflects many factors, including their preflight physiologic status, clothing worn, duration of ground standby, and the cockpit environment. Radiant heat load is high and cockpit cooling is generally limited during low-level flight, at the same time that personnel must perform critical tasks at peak efficiency. In addition, new protective equipment is greatly increasing the thermal stress experienced by aircrews. A change in cockpit-cooling specifications, therefore, appears desirable for new fighter and close-support aircraft with their demands for maximal human performance. In-flight data and laboratory studies simulating cockpit conditions indicate that heat stress can impair performance, notably the learning of new skills. This is particularly important during training and low level flight, where new or novel situations often arise and diminished ability of crewmembers to handle new tasks could present a serious problem. Approaches are needed for limiting heat exposure in current aircraft and for man-oriented design and testing of environmental control systems in future aircraft. This paper describes some of these approaches.

LIST OF SYMBOLS

c	= cockpit	T_{co}	= core temperature
ECS	= Environmental Control System	T_{db}	= dry bulb temperature
FITS	= Fighter Index of Thermal Stress	T_{dp}	= dew point temperature
g	= ground	$\bar{T}_{sk}$	= mean skin temperature
P_w	= water vapor pressure	T_{sk}(calf)	= calf skin temperature
T_{ac}	= auditory canal temperature	T_{sk}(chest)	= chest skin temperature
T_{bg}	= black globe temperature	V	= air velocity

INTRODUCTION

Humans are well adapted to dealing with heat stress under most natural conditions. Unfortunately, the aviation environment often interferes with the usual means of dissipating heat. Aircrews of high-performance aircraft must generally work while exposed to sunlight, wear multilayer clothing which restricts sweat evaporation, and suffer undesirable physiologic and performance side effects from both vasodilation and sweating. The combination of heat and other stresses associated with flight can accelerate the onset of fatigue and degradation of critical task performance.

The need to protect avionics from overheating was formerly the main criterion for specifying the cooling capacity of an aircraft environmental control system (ECS). The maintenance of a thermally stable, comfortable cockpit environment for aircrewmembers was regarded as less important, and cockpit heat was rarely recognized as a factor limiting the performance of the man-machine system. However, aircraft demand maximal mental, perceptual, psychomotor, and physiologic performance, particularly during high-speed, low-level flight when heat stress is often the highest.

CURRENT COCKPIT-COOLING DESIGN REQUIREMENTS AND PERFORMANCE

The USAF specification for ECS is reviewed here as an example of current standards (1). It is written in general terms and applies to both high-performance and transport aircraft. It states that cockpit air temperatures may not exceed 27°C during ground operations. During flight, mean air temperature in the crew compartment should not exceed 21°C, but may rise to 27°C for 30-min periods. Radiant heat is mentioned only in terms of surface temperature and touch-burn. Moisture control is covered by the statement that inlet air shall be free of entrained moisture. The document mandates a series of ECS performance tests during all phases of development from design through production sampling. Final ECS qualification involves assessment of the preproduction unit aboard aircraft in environmental chambers and during sojourns at bases selected to present extreme climatic conditions. Failure of the ECS to meet original specifications may result in system modification and/or waiver of requirements.

The present method of assessing cockpit cooling fails to consid the effect of the environment and ECS performance waivers upon the physiological status of the aircrews. Miniaturized man-mounted instrumentation now allows the monitoring of both environmental and physiological variables aboard operational aircraft as well as during dedicated climatic tests. A sensor cluster located at shoulder or head level measures dry bulb temperature (T_{db}), dew point temperature (T_{dp}), air velocity (V), and 50-mm black globe temperature (T_{bg}). Measurements from aircrew include skin temperatures (T_{sk}), core temperature (T_{co}), electrocardiogram, and voice, besides subjective questionnaires. It is useful to measure T_{db} at multiple locations around aircrewmembers and at ECS inlet (2). Data collected so far include missions by USAF aircraft with three different ECS types: simple cycle (A-10, F-5, F-111A), bootstrap (A-7D, F-4E, F-15, F-16), and a variable-geometry, air-cycle, advanced design tested aboard an F-15. Some of these data are discussed below.

The worst heat stress recorded for aircrews occurs during ground standby. Some combat scenarios dictate that the canopy be either sealed or opened at most a few centimeters while the aircraft sits without active cooling. Significant cockpit heat stress also continues following takeoff, as shown for the A-10 in figures 1 and 2. This aircraft flies close-support missions at such low altitudes that climatic heat remains a significant factor throughout flight. Climatic tests of the preproduction models have revealed inadequate cooling capacity and poor air delivery to the pilot (3). ECS inlet temperatures were rarely less than 20°C, rudder-well temperatures remained at or above 33°C. Pilots rated heat stress as a significant factor contributing to their fatigue. The ECS has since been modified and further studies are in progress.

Fighter aircraft often fly a low-level penetration leg as part of their mission. In one test, three F-4's were studied over a series of 36 low-level flights at Eglin AFB, Florida, during April-June 1978, when $T_{db, a}$ = 23-33°C. As shown in figure 3, front-seat temperatures were significantly cooler than the rear $T_{db, c}$ which was always 4°C or more above the present military standard (4).

Aerodynamic heating also affects cockpit temperature. The interacting effects of speed and altitude were shown by a series of flights (5) where an F-111A flew selected speed/altitude combinations over desert where T_{db} = 35-40°C. The ECS was set on "full cold" throughout. Equilibrium $T_{db, c}$ at 2,000-ft AGL ranged from 19.9°C at Mach number 0.6 to 25.7°C at 0.9. At 5,000 ft and Mach number 1.2, cockpit temperature was 33.4°C and still rising after 10 min, when fuel limitation ended the run. This test also clearly showed the large head-to-foot temperature difference which is characteristic of cockpits.

The F-15 and F-16 are new aircraft whose missions are primarily at medium to high altitude. Both use improved cooling technology which reportedly reduces heat stress below that seen in older aircraft, but insufficient data are available to verify the reported improved ECS performance. Recent avionics additions, however, may increase cockpit temperatures.

HEAT EXCHANGE IN THE COCKPIT ENVIRONMENT

Cockpit temperature represents a balance between ECS cooling (mass flow and inlet temperature) and heat from various sources, including climatic and aerodynamic heating, sunlight, avionics, and human metabolism. Metabolic heat (6), together with any environmental contribution, must be dissipated at the skin to prevent heat storage. Man can tolerate storage of only about 100 $W.h/m^2$, a variation of approximately 7% in body-heat content, before approaching collapse; discomfort and performance changes may appear at half that level.

Heat exchange actually occurs in the microclimate next to the human skin. Both convective and evaporative heat exchange depend upon movement of air through this microclimate; sensible heat transfer requires that T_{db} be lower than T_{sk}, while evaporation occurs only if water vapor pressure (P_w) is less than 42 torr (saturation at skin temperature of 35°C). Sunlight entering through the canopy not only increases T_{db} by the greenhouse effect, but also contributes direct radiant heating on the order of 100 W (187 kcal/h) for a clothed man (7).

Under hot conditions, cockpits often show a large longitudinal temperature difference; while the head and upper body are exposed to full solar heating, maximal cooling is often routed to the rudder-well and lap area (2). A 10°C difference occurs in some aircraft (3), and pilots sometimes experience uncomfortably cold feet while sweating profusely.

Aircrew clothing severely limits heat dissipation by impeding both convection and evaporation. The summer flight ensemble for pilots of high-performance aircraft includes cotton underwear, Nomex flight suit, anti-G suit, boots, gloves, helmet, oxygen mask, and restraint harness. The total insulation provided is 1.5-2.0 Clo, where 1 Clo is 0.155 $°C \cdot m^2/W$, approximately the value for normal indoor clothing. Flight clothing also slows sweat evaporation, with complete impermeability under the helmet, mask, boots, and areas covered by anti-G bladders.

CONSEQUENCES OF HEAT STRESS

Physiological defenses against heat include vasodilation, increased sweat secretion, and increased heart rate. Skin temperatures in the cockpit reflect both adjacent T_{db} and overlying clothes. Sweating has several undesirable side effects, including discomfort, sweat dripping into the eyes, and gradual depletion of body-fluid reserves. If excess heat is not removed, core temperature rises. For persons at rest or doing light work in heat, T_{co} = 38°C represents the average upper limit at which the body can establish true thermal equilibrium (8). Above this level, regulatory mechanisms begin to lose their efficiency and heat storage accelerates; with such "environment-driven" conditions, it is only a matter of time until T_{co} reaches 39-40°C and collapse ensues.

Impairment of mental performance is among the earliest measurable consequences of heat stress. The literature on this topic is large and often confusing, but it is clear that heat stress of the type seen in cockpits can be associated with altered learning curves (9, 10), shortened time sense (11), impaired vigilance (11), and increased error rates on tracking (10, 11). Such changes are subtle, but can be important to man in the cockpit. For example, comparison of F-4 photoreconnaissance scores in cold and hot weather demonstrated significantly less success in heat (12). Prolonged, moderate heat stress appears to accelerate mental and physical fatigue associated with flying. Heat stress also diminishes acceleration tolerance (13).

Zeller (14) studied aircraft accident rates based on 7 x 10^7 flying hours and 3,000 accidents, finding that the rate for fighter aircraft shows a peak during the hot season which does not occur in transports. While multiple factors undoubtedly contribute to this pattern, environmental heat may make a significant contribution to the fighter pattern.

A number of procedures may improve aircrew heat tolerance and thus diminish ECS cooling requirements. Adequate heat acclimatization is an important factor. Aircrews should have ready access to palatable fluids during ground intervals, and they should also realize the importance of drinking even beyond satiety. Both body cooling and rehydration are relatively slow processes, requiring from one to several hours, depending upon both the initial stress and the environment during recovery.

The limitations of current fighter/trainer cockpit cooling stimulated the recent development of the Fighter Index of Thermal Stress (FITS) (15). From a simple FITS table, flying personnel can use $T_{db,\ g}$ and T_{dp} or relative humidity to estimate heat stress in low-level flights and can determine appropriate protective measures. Although FITS is aimed primarily at training situations, similar estimates of stress effects may someday prove useful to commanders weighing combat operations in hot climates.

MAN-ORIENTED COCKPIT COOLING

The current desire to provide only a minimum of cockpit cooling poses an important question. Should the ECS insure thermal comfort for aviators, or is some lesser amount of cooling acceptable? Comfort is usually the subjective correlate of thermoneutrality, and is therefore more than a luxury. When body temperatures exceed comfortable levels, thermal tolerance becomes time limited due to gradual depletion of physiological reserves. Exposure to extremely high heat loads may be tolerated for up to 15 min if conditions return to comfort immediately thereafter, but in aircraft ground operations the 15-min period is often exceeded, and cooling after takeoff and during low-level, high-speed flight is usually less than adequate, so elevated T_{co} persists throughout the flight. Furthermore, even mild heat stress is probably associated with decreased tolerance for the other stresses of flight, including acceleration, hypoxia, and motion sickness.

New ECS designs need to consider the aircrew psychological and physiological reactions during low-level flight. A physiologically based specification is needed that requires cooling capacity sufficient to maintain $\bar{T}_{sk} \leq 35^{o}C$ with the cockpit in full sunlight and avionics on, with allowance for aircrew clothing appropriate to the aircraft's intended mission. The P_w should be $\leq$ 20 torr, and air velocity around occupants should be 0.5 to 3.0 m/s. Aircrewmembers need sufficient individual control of ECS inlet temperature, flow, and direction so that upper-body skin temperature can be kept $\leq 36^{o}C$ while foot and leg temperatures remain $\geq 29^{o}C$. Since the duration and intensity of heat stress exposure are critical, particularly to prevent nonspecific fatigue, we recommend that T_{ac} be maintained below 38.3°C for flights of less than 3h and below 37.7°C for flights of greater duration or repeated sorties totaling > 3h.

Adequate design and testing of ECS require knowledge of aircraft mission, including flight profile, required clothing, and crew workload. ECS design should allow for "worse case" conditions; i.e., ground operations and low-level, high-speed flight in hot, humid climates. Where cooling capacity is inadequate, heat can become one of the factors determining training limitations and/or combat casualties, especially for low-altitude missions. For this reason it has become imperative to develop and strictly enforce physiologically sound ECS and personal-cooling specifications.

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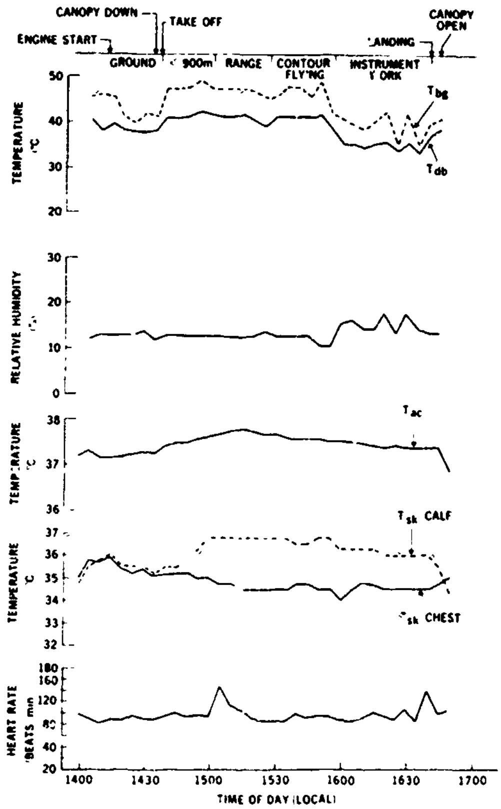

Fig. 1. Data from an unmodified operational A-10 aircraft flying over desert. Ground conditions averaged 39°C and 14% relative humidity. Sky was clear. T_{ac} = auditory canal temperature, T_{sk} (calf) = calf skin temperature, T_{sk} (chest) = chest skin temperature.

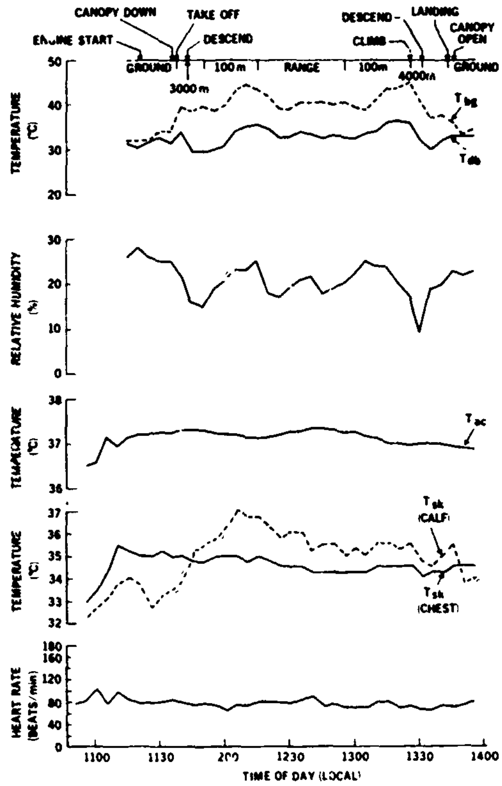

Fig. 2. Data from a modified operational A-10 aircraft over desert. Ground conditions averaged 35°C and 23% relative humidity. Sky was clear. See figure 1 for explanation of abbreviations.

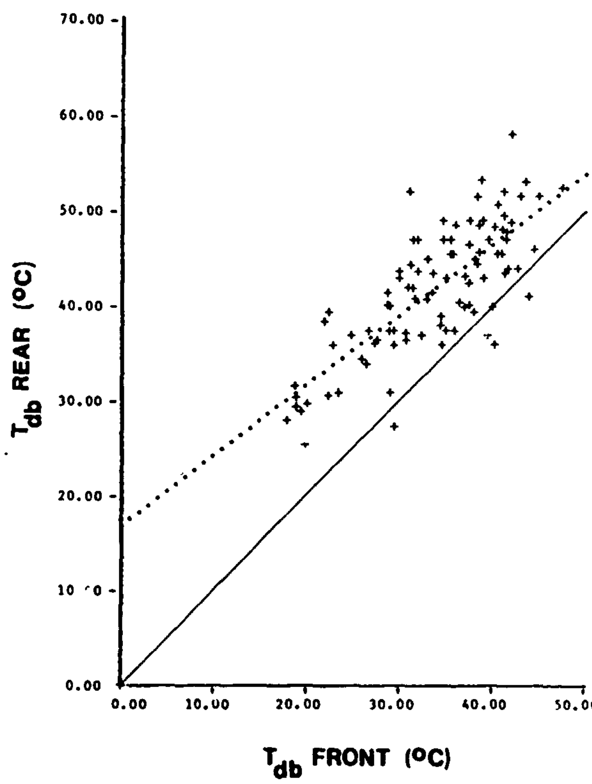

Fig 3. Relationship between rear cockpit (T_{db} rear) and front cockpit (T_{db} front) of F-4E during low-level flight. The temperatures are related by: T_{db} rear = 16.77 + .749 T_{db} front. The coefficient of determination was 0.59.

ESSAI DE QUANTIFICATION DE L'AGRESSION ENGENDREE PAR LES VIBRATIONS DE BASSE FREQUENCE

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RESUME

Du point de vue biomécanique, l'homme peut être considéré comme un solide déformable sous l'effet de stimulations mécaniques provoquées en particulier par le vol grande vitesse et basse altitude. Mais, à une stimulation physique, l'homme fournit une réponse physiologique. Il met en jeu ses masses musculaires pour lutter contre les déformations qui lui sont imposées. Selon le degré de tension de la musculature, la réponse vibratoire du sujet présente un déphasage plus ou moins important par rapport à l'oscillation qui donne naissance au mouvement. Les déformations finalement observées sont la résultante de l'action mécanique et de la réaction physiologique. Cette dernière implique une contraction musculaire striée à commande nerveuse liée par conséquent à un certain niveau d'activation des centres nerveux.

Le but de l'étude est de mettre en évidence une grandeur mécanique susceptible de rendre compte du comportement d'un sujet exposé aux vibrations. La grandeur envisagée est la masse effective (rapport complexe de la force dynamique à l'accélération). L'étude est effectuée en laboratoire, sur un primate non humain, grâce à l'utilisation d'un capteur de force et d'un accéléromètre placé au point d'application des forces. Ainsi à l'aide de mesures totalement extérieures au sujet, on objective un comportement dynamique éminemment variable tout au long d'une même agression vibratoire. L'importance des variations obtenues sur les paramètres considérés permettent maintenant d'envisager l'utilisation de la méthode pour explorer le comportement global de l'homme exposé aux vibrations.

INTRODUCTION

L'agression vibratoire mécanique à transmission solidienne, n'est certainement pas la moindre des contraintes subies par un pilote d'avion d'arme en vol à grande vitesse et basse altitude, que ces vibrations soient engendrées par les turbulences atmosphériques ou les variations de densité des masses gazeuses traversées par l'aéronef.

Dans de telles conditions, les vibrations mécaniques des structures de l'appareil sont transmises intégralement au pilote qui subit cette agression sans aucune parade physiologique préalable. Ilya donc dans le vol à grande vitesse et basse altitude un élément nouveau, qui s'ajoute aux contraintes physiques, psychiques et psychologiques, déjà nombreuses imposées au pilote. Une charge de travail importante, exercée dans de telles conditions, ne permet qu'une adaptation optimale de faible durée, avant qu'apparaisse chez le sujet, une baisse du niveau opérationnel pouvant elle-même conduire à des fins de mission difficiles sinon dramatiques.

Le but de l'étude est de mettre en évidence une grandeur physique, mécanique, susceptible de rendre compte du comportement d'un sujet exposé aux vibrations.

La grandeur envisagée est la masse effective (ou masse apparente) qui se définit comme le rapport complexe de la force dynamique à l'accélération. Les travaux ont été réalisés en laboratoire, sur un primate non humain de faible poids, en position assise sur une table vibrante, utilisée sur l'axe z.

La masse effective est mesurée, grâce à l'utilisation conjointe d'un capteur de force et d'un accéléromètre placé au point d'application des forces. L'étude de la quantification de l'énergie mécanique, absorbée par une structure biologique est abordée.

Dans le cas d'une structure industrielle, pour une excitation vibratoire donnée, la réponse mécanique suit une loi invariante dans le temps : la masse dynamique est constante. Dans le cas d'une structure biologique, il n'en est plus de même : à l'aide de mesures totalement extérieures au sujet, on objective un comportement dynamique éminemment variable tout au long d'une même agression vibratoire. Sur notre animal d'expérience, de 7 à 8 kg, les variations de masse effective sont de un à deux kilogrammes. Cette dynamique permet maintenant d'envisager l'utilisation de la méthode, pour explorer le comportement de sujets humains, exposés aux vibrations lors de vols à grande vitesse et basse altitude.

LE FAIT EXPERIMENTAL

- Une expérience simple, représentée sur la figure 1 est réalisée de la façon suivante :

- *Une masse exerce une force de 20 newton sur une balance dynamique (capteur de force) elle-même fixée sur un générateur de vibrations*

- *En absence de mouvement, pour une accélération de pesanteur constante, il existe une force statique Mg de 20 N.*

- *Pour une accélération sinusoïdale ± 1g, la masse exerce une force apparente, instantanée, comprise entre 0 et 40 N.*

- *Un amortisseur placé entre la masse et la balance fait apparaître, pour une excitation identique de ± 1g, des forces dynamiques enregistrées variables ; ce sont ces variations qui sont étudiées. Ainsi pour une même accélération, une variation de la constitution mécanique du système raideur-amortissement, à masse constante, entraîne une variation de la force dynamique en amplitude et en phase.*

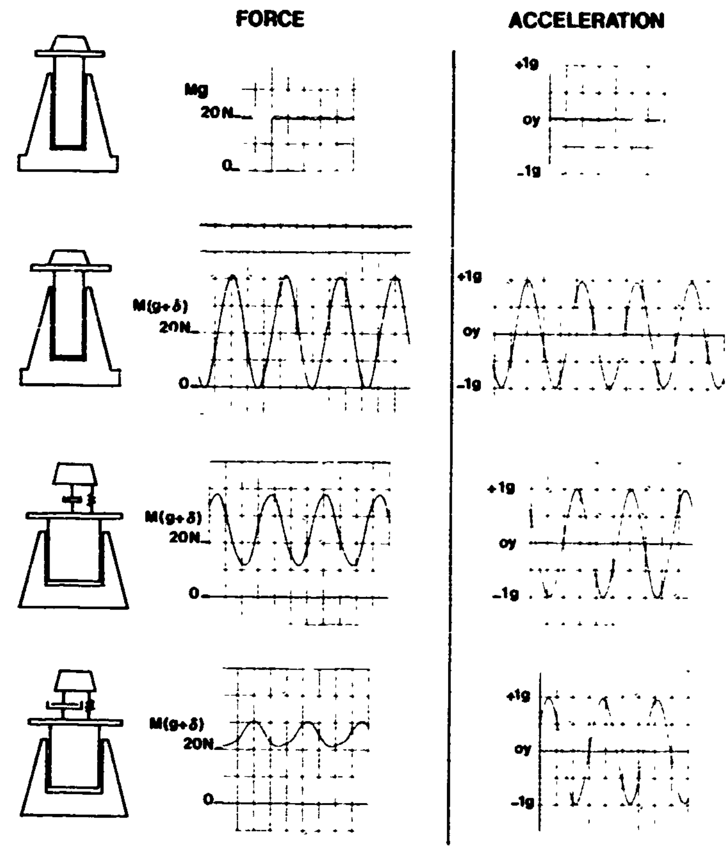


FIGURE 1

HYPOTHESES

L'homme en tant que solide déformable, subit les effets de stimulations mécaniques qui lui sont transmises par l'aéronef. Il fournit une réponse physiologiquement adaptée, notamment par la mise en jeu de ses masses musculaires, pour lutter contre les déformations qui lui sont imposées.

Les déformations finalement observées sont une résultante de l'action mécanique et de la réaction physiologique. Cette résultante est une grandeur variable qui doit être accessible à la mesure.

Les vibrations s'exerçant sur les structures d'un aéronef, dans la configuration de vol envisagée, sont aléatoires et généralement de basses fréquences. La lutte physiologique contre les vibrations dans ce domaine de basses fréquences se fait par la mise en jeu de la boucle γ après excitation active ou passive du fuseau neuro-musculaire. Cette mise en activation entraîne une dépense d'énergie, source de fatigue, en rapport avec la valeur efficace et le temps d'application du stimulus vibratoire. Dans de telles conditions, l'être humain se conduit comme un filtre. Il introduit un déphasage dans sa réponse par rapport à l'excitation.

Cette notion a donné naissance aux premiers modèles mécaniques, systèmes plus ou moins complexes de masses ressort-amortisseurs.

Ces modèles, très largement utilisés, font toujours actuellement la preuve de leur intérêt, particulièrement dans le domaine de la détermination des fréquences de résonance.

Mais ces montages mécaniques qui représentent l'être humain, comme un empilement de masses suspendues, ne prennent pas en compte la réaction comportementale des individus. Ces modèles sont invariants dans le temps. L'application de forces ou de déplacements sur une des masses du modèle entraîne une réponse toujours identique : les mêmes causes produisent les mêmes effets. Or, chez l'homme, l'application d'une force produit des effets différents, selon l'état de tension de la musculature (rigidité du sujet), le temps et le point d'application, etc... Les modèles mécaniques soumis à des vibrations simulent bien la réponse dynamique de l'homme, mais ne rendent pas compte de la variation de cette dynamique en fonction du temps.

Pourtant cette relation représente certainement au moins un des éléments (dont il convient absolument d'apprécier l'importance, de la désadaptation du pilote, soumis au stimulus vibratoire du vol grande vitesse, basse altitude.

Placé devant une structure à étudier, l'ingénieur pose une série de questions visant à déterminer la durée de vie de cette structure en réponse à des excitations connues.

- La première étude porte sur la caractérisation des sources, c'est-à-dire, sur l'estimation des fréquences excitatrices et leur niveau énergétique respectif : c'est le spectre de l'excitation, fonction de coordonnées spatio-temporelles.

- La seconde caractérise le système vibratoire (charges propres, charges permanentes extérieures, conditions aux limites, etc...). Ces paramètres ayant été determinés, le nombre de modes propres est choisi dans la bande d'excitation la plus importante. Ainsi en possession des caractéristiques vibratoires (dont certaines comme les coefficients d'amortissement sont fixés à priori pour un premier calcul), la réponse du système et les contraintes dynamiques sont estimées. Bien sûr les hypothèses de stabilité dynamique et de linearité (tout au moins au premier ordre) sont adoptées.

Considerons maintenant la réponse des structures biologiques du pilote. Pour evaluer cette reponse, le biomécanicien doit, de manière tout à fait analogue à celle de l'ingenieur, entreprendre deux types d'études :

- La première porte sur le niveau énergétique des fréquences excitatrices.

- La seconde caractérise la réponse du système.

Mais quand le système opérateur est un organisme vivant, il faut considérer les points suivants :

- Le coefficient d'amortissement n'est pas invariant dans le temps.

- La réponse d'un opérateur biologique en oscillation libre n'est pas univoque. La valeur du signal de sortie dépend sans doute de la valeur du signal d'entrée à l'instant considéré, mais elle depend aussi de l'état du système opérateur à cet instant.

Pour un même signal d'entrée F (t), la réponse sera éminemment variable d'une expérience à l'autre, car la pulsation propre ω_o

$$\omega_o = \left[\frac{k}{m}\right]^{\frac{1}{2}}$$

est variable car, si la masse m de la structure biologique est constante, il en va tout différemment de sa "raideur" k. Pour une période d'observation de durée raisonnable pour un biologiste, c'est-à-dire, pour une variation de temps suffisamment grande, les hypothèses de linéarité et de stabilité dynamique doivent être rejetées. La pulsation ω_o *et l'amortissement A restent cependant des paramètres qui caractérisent la qualité biomécanique de la réponse. Dans le cas d'un organisme vivant, les amortissements ne sont pas strictement visqueux, et les ressorts ne sont pas linéaires. Ainsi l'équation bien classique de la réponse d'un "Spring dash-pot" a une excitation* $\vec{F}$

$$M \frac{d^2x}{dt^2} + A \frac{dx}{dt} + k \quad x = F \qquad (1)$$

devient pour un opérateur humain

$$[M]\left\{\frac{d^2x}{dt^2}\right\} + [A\ (\omega_o, t)]\left\{\frac{dx}{dt}\right\} + [K\ (A \cdot t)]\{x\} = \{Y(t)\} \qquad (2)$$

Soulignons de plus qu'une telle équation ecrite sous forme matricielle implique que la théorie des masses concentrées s'applique avec une bonne précision : ce qui a été généralement admis mais ne semble pas avoir été démontré lors de la mise au point des modèles mecaniques ; (un homme peut-il être ainsi discrétisé).

On peut supposer que, dans le cas des structures biologiques, les variations en fonction du temps, de l'élasticité, de l'amortissement sont des témoins de la fatigue de l'organisme. Si de plus cette fatigue due aux vibrations est liée à la quantité d'énergie absorbée par l'opérateur et dissipée par celui-ci dans ses ressorts (muscles, système ATP-myosine) et ses amortisseurs (système ostéo-ligamentaires) alors la grandeur qu'il faut prendre en considération est une quantité globale de travail rapportée au temps, c'est-à-dire une puissance.

A la notion d'effet instantané des vibrations mécaniques sur l'homme, qui engendre une gêne ponctuelle (essentiellement liée aux problèmes des résonnances), il nous est apparu indispensable de faire une sommation de la gêne instantanée sur le temps. Ainsi à la notion de gêne se substitue la notion de fatigue liée elle-même à la notion de "dose" d'énergie vibratoire absorbée.

Si l'on fait une mesure de la réponse globale du système, alors les lois regissant les vibrations des structures industrielles, et qui sont les mêmes pour les structures biologiques, deviennent très facilement observables.

Un homme assis (figure 2) exerce statiquement sur le siège une force égale au produit de sa masse par l'accélération de la pesanteur (g).

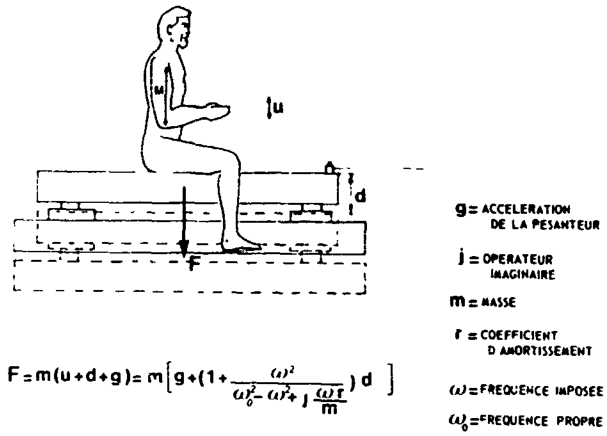
Le support soumis à une vibration, présente des mouvements qui engendrent une accélération dite d'entraînement, $\ddot{\delta}$*. La force devient égale au produitde la masse par la somme des deux accélérations (de pesanteur et d'entraînement).*

Si le sujet amortit les vibrations, il présente des mouvements relatifs, donc une accélération relative, $\ddot{\mu}$*, par rapport au siège. La force globale exercée par l'individu sur son support devient égale au produit de sa masse par la somme des trois accélérations (pesanteur, entraînement, relative). On démontre que, pour un système masse-ressort-amortisseur, la force globale s'exprime simplement en fonction des seules*

accelerations de pesanteur et d'entraînement.

Le travail d'une force est égale au produit scalaire de la force par le déplacement au point d'application de la force. Ce point d'application n'est autre que le siège du sujet dont le déplacement est connu (puisque enregistrable).

Une structure soumise à des oscillations forcées ne devient évidemment pas hyperenergétique. L'énergie appliquée est soit transmise, soit absorbée et dissipée sous forme de chaleur.



$$F = m(u+d+g) = m\left[g + \left(1 + \frac{\omega^2}{\omega_0^2 - \omega^2 + j\,\frac{\omega r}{m}}\right) d\right]$$

FIGURE 2

Mais un homme en situation d'activité ne se contente pas généralement d'être un passif dissipateur d'energie (figure 3). C'est également un transformateur d'énergie susceptible de faire varier ses contraintes internes pour lutter contre les déformations engendrées par les vibrations. On peut donc améliorer le modèle des filtres passifs par l'adjonction de filtres dynamiques, en montage série et parallèle.

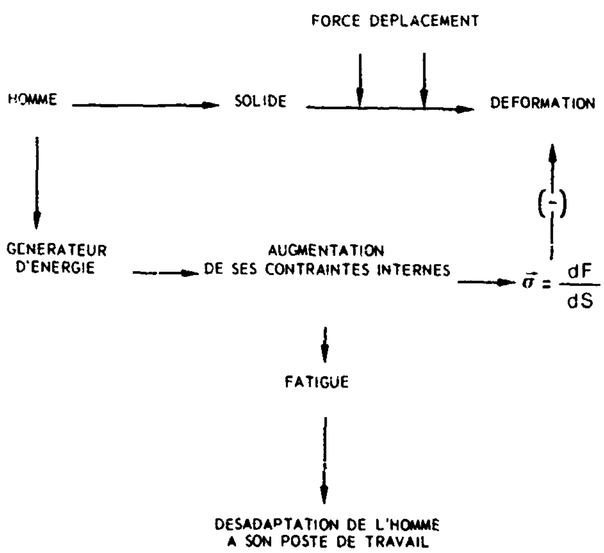


FIGURE 3

Les figures (4,a,b,c) schématisent un tel montage. Physiologiquement, la masse centrale représente les viscères qui se conduisent comme des filtres passifs. Ils présentent un coefficient de surtension en relation avec leur suspension ostéo-ligamentaire. L'amplitude des mouvements est forcement limitée par l'enveloppe musculo-squelettique.

Cette enveloppe musculaire striée est justement représentée par les masses externes qui réalisent des filtres dynamiques, réjecteurs, accordables sur les fréquences d'excitation.

Quand les structures sont parfaitement rigidifiées (limite du tétanos physiologique), le vecteur accélération relatif de l'ensemble est un vecteur nul (en dessous de 1 g) et le module des forces dynamiques est maximum.

Si les filtres réjecteurs physiologiques redeviennent efficaces (c'est-à-dire mise en jeu volontaire de la musculature striée squelettique) pour filtrer le déplacement vibratoire engendré par le support, le module de la force dynamique résultante tend vers un minimum.

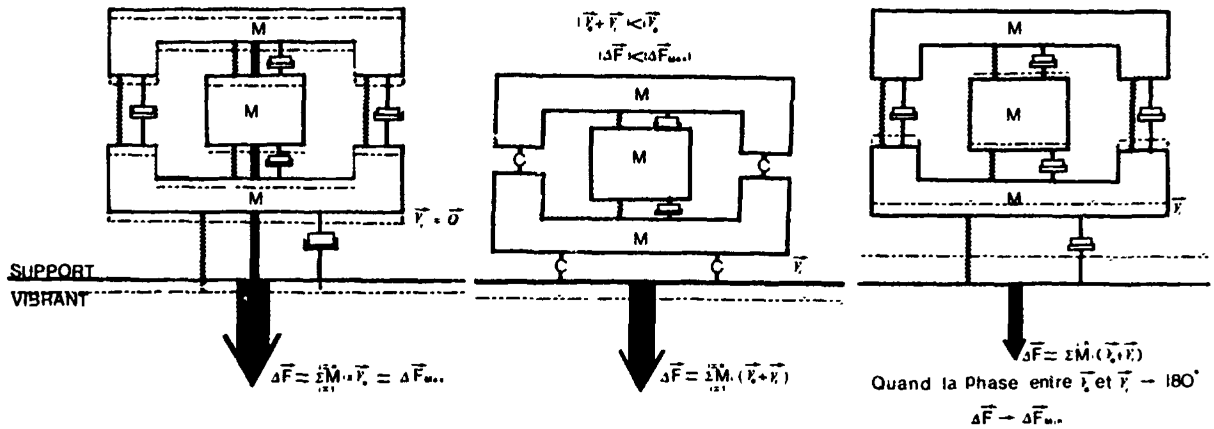


FIGURE 4

Bien entendu, entre ces deux valeurs extrêmes se placent toutes les possibilités, selon que le sujet plus ou moins rigide filtre plus ou moins les vibrations appliquées (ce qui est représenté dans la figure (4 b) par un couplage plastique des filtres réjecteurs.

Dans de telles conditions, la force dynamique varie. Il est alors possible à l'aide d'un accéléromètre et d'un capteur de force, de quantifier en N x m une dose de vibrations absorbée par un individu pendant un temps t. De plus, ayant posé l'hypothèse que la variation d'absorption dans le temps de cette énergie vibratoire par les structures biologiques du sujet est en rapport direct avec son état de tonicité musculaire, nous nous proposons de vérifier ces affirmations par l'analyse des signaux force et accélération au point d'application des forces.

METHODOLOGIE

L'étude préalable est réalisée en laboratoire sur un primate non humain, babouin de 6 à 8 kg. L'animal assis dans un siège de contention est soumis à une excitation vibratoire.

La vibration engendrée est généralement un signal sinusoïdal pour l'étude des effets de la contraction musculaire et un bruit blanc à bande étroite pour les études de traitement de signal (Transformée de Fourier, fonction de transfert, fonction de cohérence).

La fréquence de résonance d'un animal de 6 à 8 kg a été estimée en fonction des considérations suivantes :

- La fréquence de résonance globale d'un sujet humain est d'environ 3 Hz (variable selon l'état de conscience ou de rigidité de l'individu). Au-delà de 30 Hz (10 fois la grandeur fondamentale), on n'observe plus que des fréquences de résonance intéressant des organes très particuliers, (exemple : le globe oculaire). En prenant arbitrairement une "raideur" identique chez l'homme et le singe, on apprécie la fréquence de résonance de ce dernier par simple rapport.

$$N_S = \left[\frac{(2\pi N_H)^2 \times 60}{(2\pi)^2 \times 8}\right]^{\frac{1}{2}} = 8{,}2 \text{ Hz}$$

N_H : fréquence de résonance de l'homme
N_S : fréquence de résonance du singe
masse de l'homme : 60 kg
masse du singe : 8 kg

Ainsi, en travaillant dans une bande de bruit de 0 à 100 Hz, on étudie la réponse physique de l'animal jusqu'à la 10^e harmonique.

Une telle étude impose :

- Un capteur de force placé en série entre le support vibrant et le siège de contention de l'animal
- Un accéléromètre
- Une instrumentation nécessaire à la création du signal vibratoire excitant l'animal. Tête d'excitation Bruel et Kjaer 4808
- Un ensemble de conditionnement des signaux acquis
- Le traitement analogique et numérique des observations recueillies :

- Traitement analogique :

- calcul en temps réel de l'énergie effective, en utilisant deux intégrateurs et un multiplicateur tel que :

$$W = \int_{r_1}^{r_2} F.\,dr = \int_{t_1}^{t_2} F\,v.dt.$$

r déplacement
v vitesse

- Les valeurs efficaces de l'accélération et de la force après filtrage des composantes continues, c'est-à-dire, après avoir fait abstraction de l'accélération de pesanteur et du poids de l'animal.

- Le traitement numérique étudie :
  - la masse dynamique de l'animal, en faisant le rapport des Transformées de Fourier, des signaux force et accélération (fonction de transfert F/γ)
  - le déphasage force vitesse
  - la puissance mécanique absorbée par l'animal.

PROTOCOLE EXPERIMENTAL

- *MISE AU POINT D'UN SIEGE DE CONTENTION (FIGURE 5)*

La forme du siège conditionne la position de l'animal soumis à l'agression vibratoire. Cette position doit être la plus physiologique possible. Il est nécessaire d'éviter la survenue de contractions musculaires à visées antalgiques qui perturberaient gravement l'etude. Le buste de l'animal est relativement stabilisé pour éviter les mouvements de grande amplitude, particulièrement dans les directions antéro-postérieures, latero-laterales et les mouvements de rotation. L'animal peut faire reposer ses membres sur un plan dur. La frequence de résonnance du siège se situe loin de la frequence de résonance globale du singe. Construit en NIDA ET RESINE PROCHAL LY 560, il ne présente pas de mode de vibrations engendrant des stimuli vibratoire secondaire dans la bande sonore ou infrasonore, et sa fréquence propre est superieure à 80 Hz.

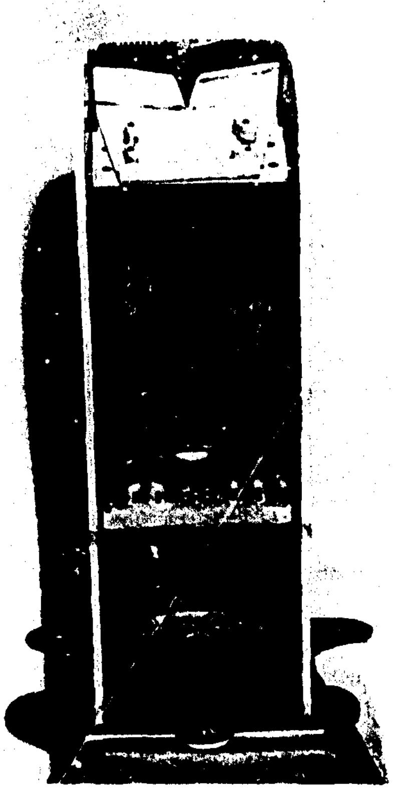


FIGURE 5

FIGURE 6

- *LA TABLE VIBRANTE ELECTRODYNAMIQUE (FIGURE 6),*

C'est une table Bruel et Kjaer type 4818 "Big Head Table" inserée dans une boucle de regulation, qui comprend un générateur de fonction type 1026, un amplificateur de puissance type 2708, un accéleromètre type 4332, un amplificateur conditionneur type 2626. L'excursion totale de la table (crête à crête) est de 19 mm. Lorsqu'on désire faire vibrer une structure matérielle (un animal dans notre étude) de masse M sous une accélération γ, la force requise est $F = M\gamma$. Mais il faut tenir compte également de la somme des masses de l'equipage mobile, moyens de contention de l'animal, plateau, capteurs de force etc...
Or la force dynamique limite de la table est de 1780 N,
soit : $1780 = \gamma\ (M + \Sigma\ m_i)$.

Il existe donc des limites physiques de l'ensemble en fonction de la frequence.

Pour les fréquences inferieures à 20 Hz, d'autres facteurs doivent être pris en compte ; le deplacement par exemple, doit être maintenu au-dessous de 19 mm, c'est pour que l'équipage mobile n'entre pas en contact avec les butées de limitation de fin de course. Entre 20 et 100 Hz, ce sont les grandeurs electriques maximales admissibles (courant de 43 A) qui interviennent.

L'expérience a montré que la seule immobilisation de l'ensemble vibratoire, liee uniquement au poids de l'appareil ($\simeq$250 kg) faisait apparaître des fréquences de résonance parasites aux environs de 12 Hz et de 21 Hz. C'est pourquoi il a été nécessaire d'augmenter la masse totale vibratoire, par adjonction d'une

masse sismique de 4 tonnes de béton. Dans cette masse ont éte noyées des poutrelles de fer soudées en croisillons et immobilisées, de telle sorte que la base du pot vibrant soit parfaitement horizontale.

Ainsi la nouvelle fréquence de résonance de l'ensemble se situe en-dessous de 1,5 Hz, c'est-à-dire, très en deçà de notre gamme de travail.

Dans les conditions normales d'utilisation :
- la masse du capteur de force installée sur la tête d'excitation est de 20 kg,
- la masse de l'animal est approximée à 8 kg,
- la masse du siege est de 4,250 kg.
Soit une charge totale de 320 N (approx.).

Comme l'accélération maximale (crête-crête) ne sera jamais supérieure à 0,5 g dans notre experience, pour eviter que la tête d'excitation ne vienne en butée sur le silent-bloc et detruise ainsi le capteur de force, la force maximale developpée par le pot vibrant a ete ramenée à 1000 N (disjonction au delà de cette valeur).

- LE CAPTEUR DE FORCE (FIGURES 7 ET 8)

Realisé en AU 4G, il se compose d'un plateau supérieur, d'un plateau inférieur, de trois ailes, d'une plaque inférieure et de trois dynamomètres.

Entre les deux plateaux sont pris en sandwich, les trois dynamomètres dont les corps d'épreuves supportent des jauges à semi-conducteurs . Elles delivrent, par l'intermediaire d'un pont de jauges, des tensions proportionnelles aux forces. La sommation analogique des trois dynamomètres donne la force globale exercée sur le plateau supérieur.

La plaque fixée au centre du plateau superieur permet par démontage rapide, de fixer un accélerometre dans la cavité centrale.

Les trois éléments sensibles sont des capteurs de force modele N.T.C, fabriques et commercialisés par la Societé F.G.P. Instrumentation ; les caractéristiques montrent :
Une étude de mesure : 100 daN
Dérive en température : 0,1 %/°C
Flèche sous charge : 0,0254 mm
Fréquence de resonance : 5,5 KHz

Chaque élément sensible constitue un pont de jauge complet. Les signaux obtenus sur les éléments unitaires sont amplifiés au niveau d'un premier étage constitué de trois amplificateurs analogiques d'instrumentation à entrées différentielles.

La sensibilité est particulière à chacune des voies. Le gain des amplificateurs a eté adapte pour que le niveau nominal de chacun des capteurs de force du tripode a l'entree de l'étage suivant, soit très exactement ajusté à 100 mV/daN

L'étage suivant est constitué d'un sommateur sur les entrees auxquels sont connectes :
- les trois éléments unitaires du capteur de force,
- les contre tension de - compensation statique
- compensation dynamique

Au niveau du sommateur, un préamplificateur à gain variable permet l'ajustement du zero électrique.

La compensation statique est réalisée grâce à l'ajustement potentiométrique d'une contre tension dont la valeur absolue est égale à celle qui represente la valeur des masses placees sur le capteur de force. D'autre part, la fixation du siège de contention sur le plateau supérieur du capteur de force se fait par boulonnage serré de ces deux éléments. Une telle solidarisation cree des contraintes dans le metal. Elles sont enregistrées au niveau des élements sensibles du capteur de force comme une tension continue (reflet des inévitables disparités mecaniques d'usinage). Cette tension continue est annulee. Dans le cas contraire elle interdirait l'utilisation du tiroir calcul par mise en saturation des intégrateurs.

La compensation dynamique a pour but d'éliminer les forces dynamiques stables, c'est-a-dire, celles qui ne sont pas liees aux variations d'amortissement d'origine biologique. (Elles-mêmes en rapport avec les accélérations relatives).

Cette compensation est réalisee en multipliant la valeur des masses statiques, (appropriation du gain d'un amplificateur aux masses à compenser) par l'inverse de la valeur de l'accélération.

Ainsi, tout élément réglé (zero mécanique = zéro électrique), la mise en route du plateau vibrant, quelles que soient la fréquence et l'accélération choisies, doit délivrer une tension nulle en sortie de sommateur.

Dans de telles conditions, les tensions obtenues après sommation représentent des variations d'accélérations relatives. Le gain de ce signal dynamique est ajusté à 100 mV/daN.

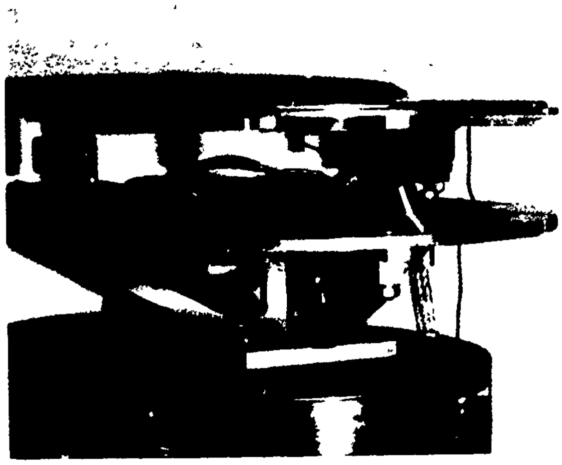


FIGURE 7

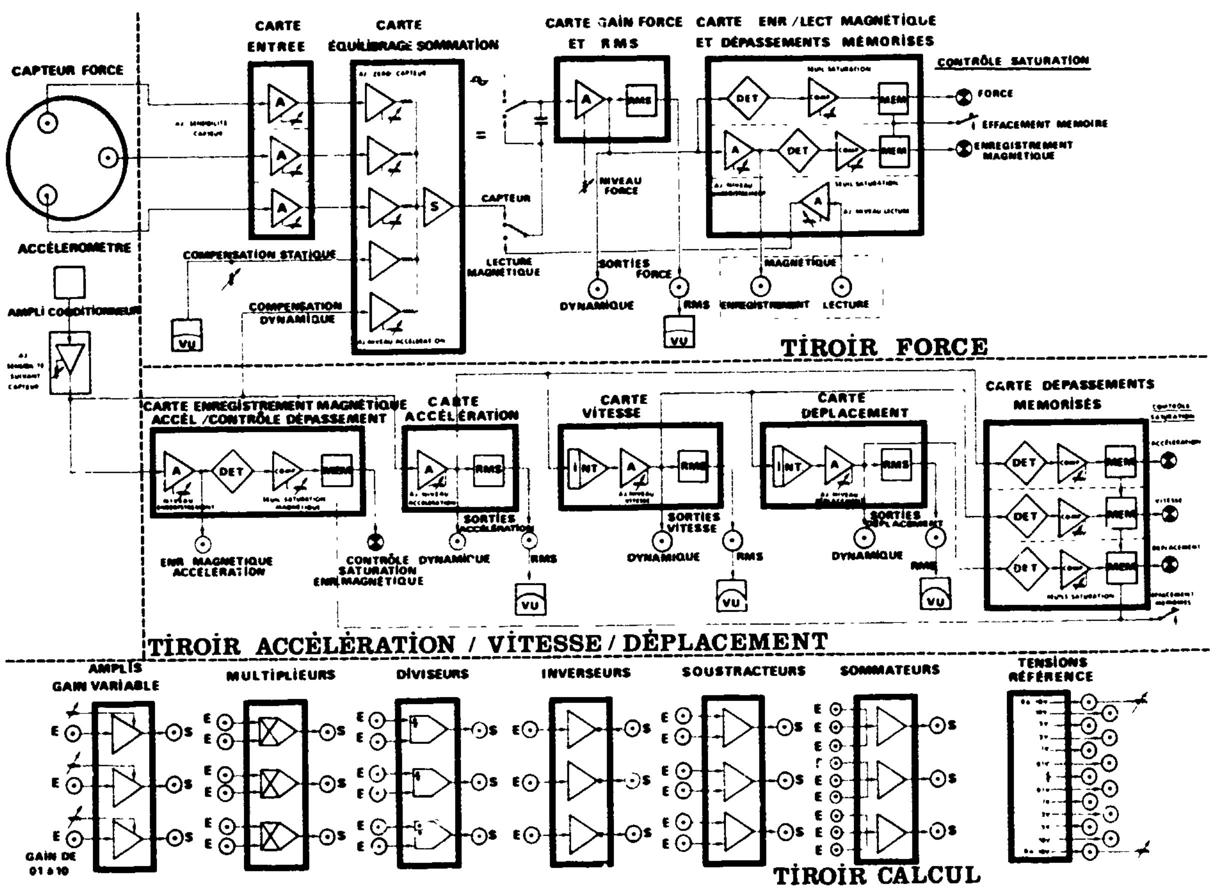


FIGURE 8

- L'ACCELERATION AU POINT D'APPLICATION DES FORCES

Les considérations suivantes ont fait porter notre choix sur l'utilisation des capteurs accélérométriques piezoresistifs (type ENTRAN ECG 500 DS 10) :

- *Impédance de sortie faible.*
- *Bon rapport signal/bruit.*
- *Facilité d'étalonnage.*
- *Stabilité en température.*
- *Excellent comportement en cas de surcharge.*

Cette dernière caractéristique est très importante dans le cadre de cette étude. Il est, bien sûr important de travailler au maximum de la dynamique du capteur pour optimiser le rapport signal sur bruit. Or, nous avons déjà souligné qu'en biologie, les systèmes ne sont pas dynamiquement stables. Ceci signifie qu'à tout instant les accélérations infligées par l'animal au capteur peuvent non seulement être supérieures à leur valeur maximale, mais peuvent prendre l'allure de chocs. Nous serions alors obligés de

travailler à bas niveau avec des capteurs a grande dynamique, donc avec un mauvais rapport signal/bruit.

L'accéléromètre utilise optimise ce rapport pour une etendue de mesure de 10 g (deplacement de 2 mm crête à crête à 50 Hz, sinus) tout en admettant un dépassement sans detérioration de plus de 10 fois sa valeur maximale.

Le signal accélérometrique conditionné, étalonne à 100 mV/m/s^{-2} est alors disponible selon deux modes (non exclusifs) :

- *Enregistrement sur magnetique d'instrumentation.*
- *Poursuite en ligne du traitement du signal accélérométrique (intégrations répétees pour obtention de la vitesse et du déplacement du capteur de force).*

Les valeurs efficaces de ces trois parametres (accélération, vitesse, deplacement sont disponibles à chaque étage, soit en phase, soit en inversion de phase.

Le traitement numerique du signal n'appelle pas de remarque particulière puisqu'il est réalisé "en ligne" après ajustement des niveaux, par analyse en temps réel sur analyseur "Spectral Dynamics 360".

Dès lors, l'etalonnage du montage expérimental est le suivant :

a) - Etalonnage de la chaîne d'excitation B et K
- *Etude du spectre du signal vibratoire en mode sinusoïdal ou en bande de bruit de 100 Hz.*
- *Etude de la régulation par compression.*
- *Etude des accéléromètres.*

b) - Etalonnage de la mesure d'une masse
- *Etalonnage du capteur de force*
  - *Etalonnage statique : après mise en place de masses marquees sur le capteur de force, les forces enregistrées sont comparées à celles qui sont exercees par les masses connues (étalonnage statique).*
  - *Etalonnage pseudo-statique : observation de l'évolution de la valeur moyenne de la force développée par une masse connue, soumise à un deplacement rectiligne sinusoïdal.*
  - *Etalonnage dynamique : différentes masses marquées sont placées tour à tour sur le plateau. Un mouvement rectiligne sinusoïdal asservi sur l'accélération est appliquée à la masse. Les forces dynamiques correspondantes sont enregistrées en fonction du temps. Leurs valeurs efficaces sont relevées.*

c) - Stabilité des résultats en condition normale d'utilisation
- *Une masse connue est soumise à une vibration dont l'amplitude de l'accélération est déterminée. Les valeurs enregistrées sont comparees aux valeurs calculées.*

d) - Etude de la masse dynamique
- *Mesure du rapport de la force instantanée à l'accélération instantanée d'une masse de valeur connue, placee au centre du plateau.*

Les moyens mis en oeuvre pour etudier les variations de masse dynamique et de l'absorption de l'énergie vibratoire d'un animal en fonction de son niveau de tonicite musculaire sont decrits dans le rapport N°3399 EASSAA/CERMA/RECH (1979) (QUANDIEU et coll.). La coherence de cet ensemble étant prouvé, l'expérimentation animale s'effectue selon le protocole suivant (figure 9) :

- *Anesthésie de l'animal à la ketamine.*
- *Fixation de l'animal sur le siège de contention.*
- *Fixation du siège sur le capteur de force.*
- *Branchement de l'appareillage mécanique et electronique.*
- *Attente d'une heure pour obtenir la stabilisation en temperature du montage electrique et électronique.*
- *Vibration de l'animal conscient, puis anesthesie en fin d'expérience avec enregistrement:*
  - *de la force dynamique,*
  - *de l'accélération au point d'application des forces,*
  - *de la masse dynamique,*
  - *de la fonction de transfert (en module et en phase),*
  - *de la fonction de cohérence.*

L'experience est suivie "en continu" par enregistrement analogique sur enregistreur papier GOULD 2600.

L'enregistrement sur magnétique analogique permet de calculer en différé l'énergie absorbée à partir de la fonction d'intercorrélation force vitesse.

RESULTATS - INTERPRETATION

En prealable à l'expérience, on a réalisé sur un animal, à titre de vérification, une étude de transmissibilité de l'accélération du siège vers la tête. La fixation de l'accéléromètre sur la voute crânienne est realisée très classiquement par solidarisation du capteur avec du ciment dentaire (Texton) collé et visse sur la table externe.

Les enregistrements 10 et 10 bis présentent les transmissibilités obtenues chez un animal éveillé, puis chez le même animal anesthésié au Nembutal IV excité en bande de bruit de zéro à 100 Hz.

Le tracé inférieur représente le module de la fonction de transfert, le tracé supérieur la phase. L'animal éveillé se comporte effectivement comme un filtre passe-bas dont la diminution d'amplitude à 3 dB se situe très grossièrement vers 60". Après anesthésie s'inscrit une résonance vers 15 Hz qui n'apparaissait pas clairement dans le cas de l'animal tonique. Ceci montre bien que le filtrage réalise par l'animal varie selon que ce dernier est éveillé ou endormi. On constate d'ailleurs une variation de la pente de la phase,

sans que l'on puisse dans l'avancement actuel de nos travaux préciser s'il existe une relation entre module et phase.

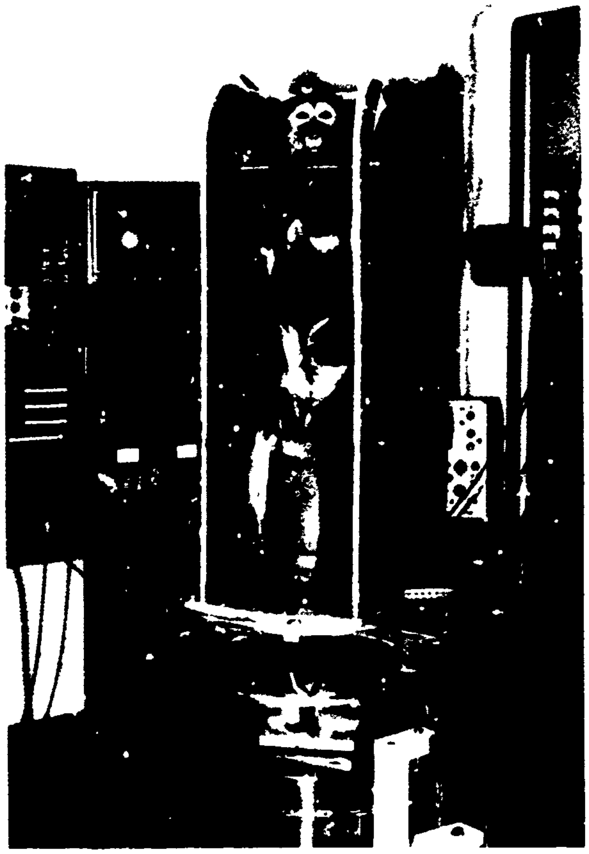


FIGURE 9

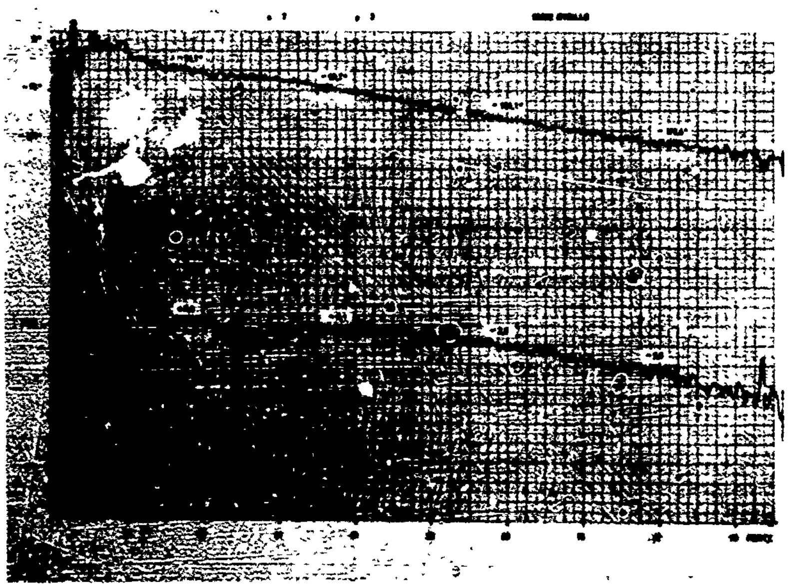


FIGURE 10

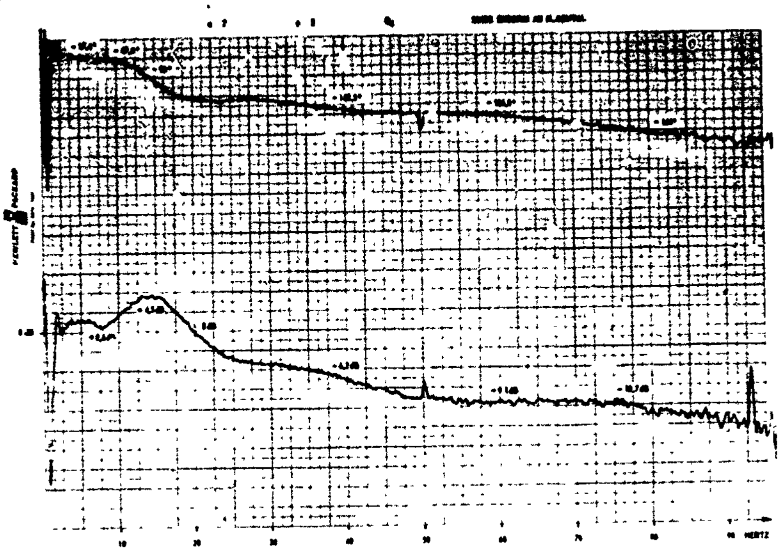


FIGURE 10 BIS

Dans le cas particulier de ces etudes de transmissibilite, une telle relation est particulierement délicate à mettre au point car le module est directement fonction de l'angle d'inclinaison des deux accelerometres par rapport à la direction privilégiee de l'espace.

Dans l'étude de la masse dynamique, les deux capteurs (capteurs de force et accelerometre) sont situés au même endroit. De plus, ils sont solidaires l'un de l'autre. Cette étude du rapport complexe de la force à l'accélération peut se faire à fréquences variables ou à fréquences fixes.

L'étude a fréquence variable de la masse dynamique du siège de contention chargé par une masse marquée de 7 kgs est préalablement effectuee. Elle a pour but de vérifier la validite des mesures. Le signal d'excitation est une bande de bruit de largeur 100 Hz (figure 11). La masse dynamique est obtenue en faisant le rapport des Transformees de Fourier des signaux force et accélération (fonction de transfert F/γ). On constate que le module de la masse dynamique (tracé inférieur) est constant en basse frequence. A 60 Hz, il existe une augmentation de 1 dB qui prouve l'amorce d'une résonance de ce systeme inerte intervenant au délà de 100 Hz.

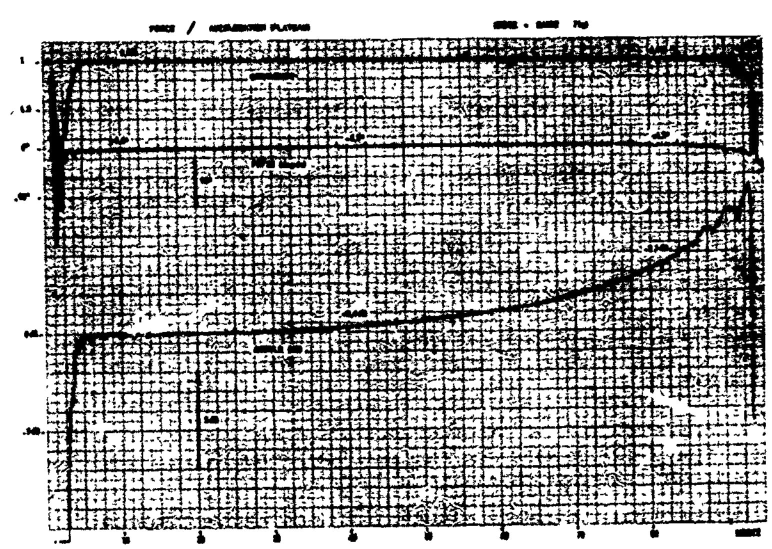


FIGURE 11

L'enregistrement représenté sur la figure 12 donne le graphe de la masse dynamique d'un babouin anesthésié, maintenu dans le siège de contention en fonction de la fréquence. Ce qui est effectivement noté, c'est en fait, le rapport 20 log (F_{elect}/γ_{elect}). En effet, les grandeurs qui sont effectivement mesurées, sont des tensions respectivement représentatives des force et accéleration.
La sensibilité choisie du capteur de force est de 10 mV/hgf.
On en déduit que : F (volt) = kF $\qquad k = \frac{0,}{9,806}$ Volt/N

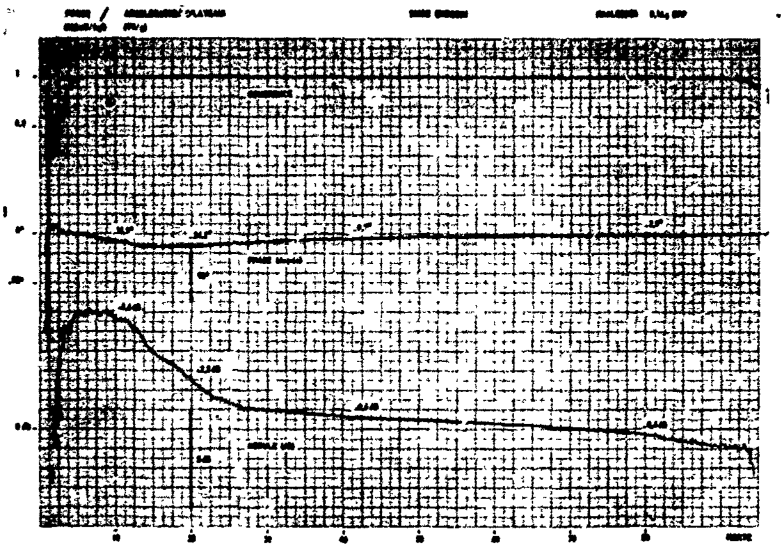


FIGURE 12

De même, la sensibilité de l'accéléromètre est de 1V/g.
On en déduit que :

$$\gamma \text{ elect (volt)} = k'\gamma \qquad k' = \frac{1}{9,806} \text{ volt/m/s}^2$$

Ainsi :

$$20 \log \frac{F \text{ (elect)}}{\gamma \text{ (elect)}} = 20 \log \frac{h}{k'} 0,1 \frac{F}{\gamma}$$

On voit que :

$$20 \log \frac{F \text{ (elect)}}{\gamma \text{ (elect)}} = + 4 \text{ dB à } 15 \text{ Hz}$$

Alors :

$$20 \log 0,1 \frac{F}{\gamma} = 4$$

$$\text{et } \frac{F}{\gamma} = 15,8 \text{ kg}$$

Cette masse comprend aussi bien sur, la masse du siège, celle du plateau superieur et une partie de celle des éléments sensibles du capteur de force.

Cette masse "siège" est déterminée de la même façon, à partir du graphe obtenu, en etudiant la masse dynamique du siège non chargé. La masse "siège" ainsi évaluée est comprise entre 9,3 kg et 9,5 kg.

Dans ces conditions, à 15 Hz, la valeur de la masse dynamique du siège est égale à 15,8-9,4 = 6,4 kg, alors même que la masse statique de l'animal est de l'ordre de 8 kg.

Aux fréquences élevées le rapport $\frac{F}{\gamma}$ *décroit. Il atteint sur le tracé une valeur de 0 dB* ($20 \log 0,1 \frac{F}{\gamma} = 0$ dB $\Rightarrow \frac{F}{\gamma} = 10$ kg) *vers 70 Hz. L'animal filtre alors parfaitement les vibrations. La masse dynamique tend vers zéro. L'amplitude crête à crête de la force exercée par l'animal sur son support décroit comme sur le dernier tracé de l'enregistrement du fait expérimental (figure 1). Une décroissance apparente de la masse dynamique est observée en dessous de 5 Hz. La chute de la fonction de cohérence dans cette bande de fréquence (0 à 5 Hz) indique clairement la non validité de la mesure. En effet, un système d'excitation électrodynamique ne permet pas l'exploration des fréquences inférieures à 4 ou 5 Hz. En réalité, comme un filtre passe-bas, à très basse fréquence, la masse dynamique tend vers la masse totale du système, environ 17 kg (+ 4,6 dB).*

Dans l'étude à fréquence fixe, le signal d'excitation est sinusoïdal à 15 Hz, donc dans une zone de réponse de l'animal (cf. figure 12) et dans une zone où l'amplitude de la reponse du siège, en fonction de la fréquence est constante (cf. enregistrement n° 11).

Les expériences sont menées conformément au protocole cité (page B9-6) :

- *Anesthésie douce de l'animal à l'imalgène intraveineuse (7,5 mg.kg).*
- *Mise en place du babouin dans le siège de contention.*
- *Attente une heure : éveil de l'animal avec stabilisation en température de l'electronique.*
- *La durée de l'exposition aux vibrations est variable selon l'etat de nervosite de l'animal (généralement de une à trois heures).*

Les valeurs efficaces de l'accélération et de la force sont tracées après filtrage des composantes continues, représentées par l'accélération de la pesanteur et le poids de l'animal. L'étalonnage de la force efficace, effectué en fin de manipulation (figure 13) est obtenu en remplaçant l'animal par des masses marquées de 2, 3, 4, 5 kg etc... Cette façon de procéder nous permet de déduire la valeur de la masse effective, exprimée en kg à partir de l'enregistrement de la force. Nous parlerons ainsi indifféremment de force ou de masse dynamique, puisque l'accélération est maintenue constante tout au long de l'expérience. Le déphasage force-vitesse est également relevé ainsi que la puissance mécanique absorbée par l'animal. Plus précisément,

on calcule la valeur de la fonction d'intercorrélation force-vitesse prise à l'origine des temps.

$$C_{f.v}\,(\zeta.t) = \frac{1}{T}\int_{-\frac{T}{2}}^{+\frac{T}{2}} f(t)\quad v(t-\zeta)\; dt$$

Si f(t) et v(t) sont les forces et les vitesses instantanées, alors :

$$C_{f.v}\,(O,T) = \frac{1}{T}\int_{-\frac{T}{2}}^{+\frac{T}{2}} f(t)\quad v(t)\; dt$$

est la puissance moyenne absorbée par le système pendant le temps T.

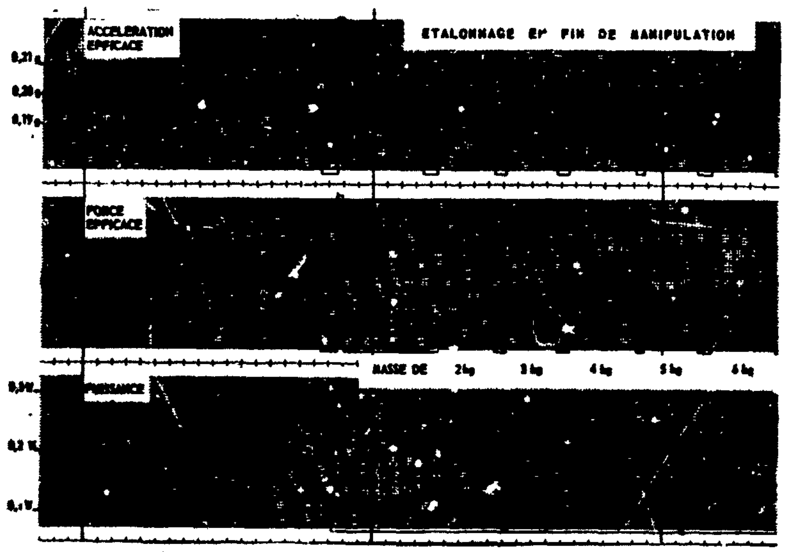


FIGURE 13

La figure 14 montre les résultats obtenus chez un babouin soumis à une agression vibratoire sinus, 15 Hz, de 0,20 g efficace. On observe d'emblée que la masse dynamique de l'animal varie entre 3 kg et 6 kg, donc une variation de 3 kg <u>uniquement</u> en relation avec son etat de contraction. Cette grandeur est extrêmement importante au regard du poids statique de l'animal egal à 8 kg. S'il se comportait comme un bloc rigide, une brique de 8 kg par exemple, la masse dynamique serait évidemment constante et égale à 8 kg. L'allure légèrement ascendante du tracé de la force efficace mérite d'être remarquee. Elle ne s'accompagne pas d'une modification apparente du comportement de l'animal : posture, tonus, etc... La mesure est probablement plus fine qu'une observation visuelle. Une etude très interessante est celle qui met en relation la puissance absorbee par l'animal, la masse efficace et le déphasage force-vitesse.

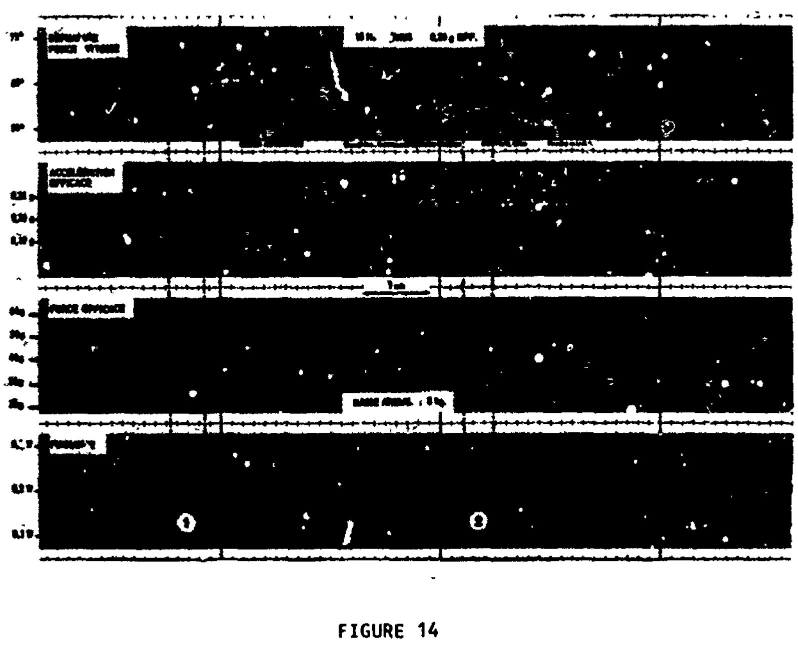


FIGURE 14

Sur la partie du trace notée 1, on constate une augmentation de la puissance absorbee en relation avec une baisse du dephasage, la force efficace etant relativement constante. Dans la partie notée 2, la puissance absorbee diminue en relation avec une baisse de la force efficace, le dephasage reste relativement constant. Dans la partie notee 3 (figure 15), la force diminue, la phase diminue, les deux effets sont opposes, l'energie dissipée varie peu.

Dans le cas ou l'animal est d'une taille suffisante pour que ses pieds prennent appui directement sur la table vibrante, il apparaît une diminution tres importante de la masse dynamique qui tombe à 2 kg. L'animal filtre alors tres bien les vibrations à l'aide de ses membres inferieurs, alors que la puissance dissipee tombe a 120 mW et que le dephasage force-vitesse augmente.

Le resultat le plus évident de cette experience est que les hypothèses strictement mecaniques concernant l'utilisation d'un accéléromètre et d'un capteur de force pour tester en continu et a l'exterieur le tonus musculaire d'un individu soumis a des vibrations sont parfaitement verifiées.

Les variations de la masse dynamique, d'un animal de faible poids soumis a des oscillations de faible energie sont importantes (environ deux kilogs dynamiques pour 8 kg statiques. Il est donc parfaitement licite de faire maintenant les enregistrements chez l'homme. Un tel résultat serait particulierement utile dans le cas du vol à grande vitesse et basse altitude. En effet, le pilote exerce le plus souvent une force résultante perpendiculaire au plan du siège. Les énergies vibratoires engendrees dans cette configuration de vol étant importantes, on peut penser que l'une quelconque des grandeurs, masse apparente, déphasage force-vitesse, puissance absorbee, ou les trois à la fois, donneront des renseignements très précieux sur l'état physique du pilote, voire même de son niveau de conscience.

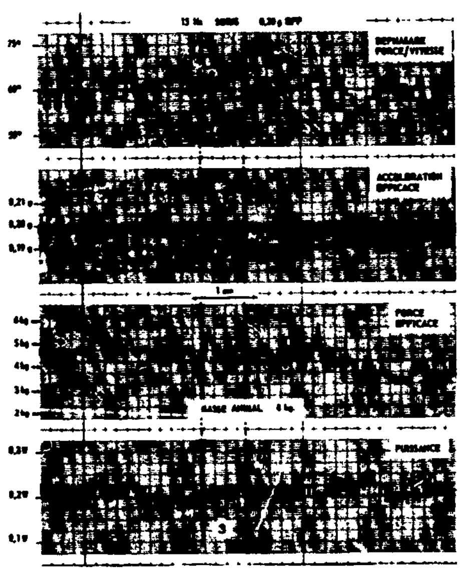


FIGURE 15

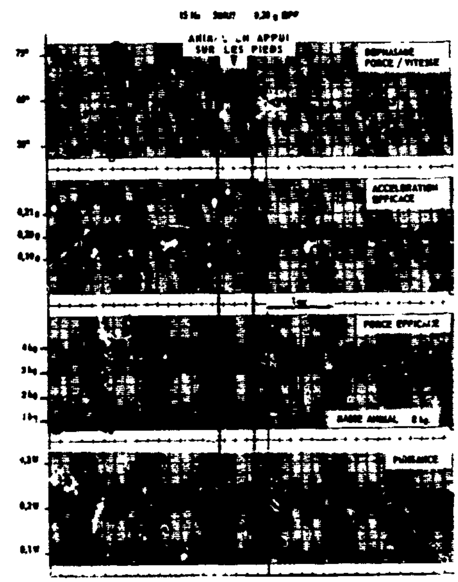


FIGURE 16

L'interprétation biomécanique de ces résultats est particulièrement délicate. En effet, les experiences montrent qu'un filtrage par les membres inférieurs (fig. 16) provoquent une diminution de la puissance absorbee. Ce qui est parfaitement cohérent avec les données des enregistrements 14 et 15.

Cependant, une structure biologique vivante et consciente ne présente aucun des caractères mathématiques de linéarité, de stationarité, de causalite qui permettraient une interprétation simple des resultats Une expérimentation conduite chez l'homme permettrait au moins de lier une cause connue et exprimee par le sujet à un effet reconnu et interpréte par l'expérimentateur : ce qui est impossible dans le cas où le sujet d'expérience est un animal.

CONCLUSIONS

Dans le cas d'une structure industrielle, pour une excitation vibratoire donnée, la réponse mecanique suit une loi invariante dans le temps. Dans le cas d'une structure biologique, il n'en est plus de même. Profitant de cette opportunité concernant la variance des resultats, on a pensé pouvoir suivre le comportement dynamique d'un pilote en vol à grande vitesse et à basse altitude à l'aide de mesures totalement exterieures à l'individu. Ces mesures effectuées à l'aide d'un capteur de force et d'un accéléromètre placé au point d'application des forces permettent de calculer les valeurs des masses dynamiques (définies comme le rapport complexe de la force à l'acceleration), le déphasage force-vitesse et la puissance dissipee dans les amortisseurs biologiques.

Une expérience préalable a eté effectuée sur un animal, primate non humain, assis dans un siège de contention. Les données experimentales montrent le bien-fondé des hypothèses et la coherence des résultats

obtenus. En particulier, l'étendue de mesure concernant les variations de masse dynamique nous incite à penser qu'il est judicieux d'utiliser cette technique pour suivre non seulement l'état physique mais également le niveau de conscience d'un pilote soumis à une agression vibratoire à transmission solidienne.

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DISCUSSION

DR. J. CLEMENT (BE)

Pourquoi avoir employé un bruit blanc comme signal d'excitation plutôt que des signaux sinusoidaux séparés puisque le système n'est pas linéaire?

AUTHOR'S REPLY

Nous utilisons une excitation en bruit car elle fournit un bon test de linéarité et une approche réaliste pour l'étude des vibrations mécaniques en biologie.

1 - Le système mécanique constitué par l'animal possède à priori une plage
   |où il est linéaire
   |de linéarité.

2 - 2a : Dans le cas d'une excitation sinusoïdale pure, la fonction de cohérence entrée-sortie peut avoir une valeur égale à 1 à la fréquence d'excitation, que le système considéré soit linéaire ou non linéaire.

   2b : En fait, l'excitation n'est jamais purement sinusoïdale (distorsion du pot vibrant). Le "système animal" est alors excité par un spectre de raies harmoniques. Si le système est linéaire, la cohérence est égale à 1 pour toutes les fréquences d'excitation, elle vaut 0 partout ailleurs. Si le système est non linéaire, elle peut toujours valoir 1 sur le fondamental. Elle décroit plus ou moins sur les harmoniques, suivant l'importance de la non linéarité. Ainsi, pour une excitation dont le fondamental est à 60 Hz, la distorsion se manifeste à partir de 120 Hz, ce qui n'est pas visible si nous observons la bande de 0 à 100 Hz. Ce test de linéarité est alors valable à condition d'avoir une bande de fréquence d'observation dépassant largement la bande d'excitation. On perd alors en pouvoir de résolution.

   2c : Dans le cas d'une excitation en bande de bruit 0-100 Hz, la cohérence est de 1 dans la même bande si le système est linéaire. Par contre, une nonlinéarité entraîne une distorsion par intermodulation faisant chuter la cohérence dans la même bande. Nous disposons ainsi d'un bon test de linéarité. C'est une raison pour choisir l'excitation par bruit.

3 - Le comportement de l'animal dépend du spectre d'excitation, et risque de varier en fonction de celui-ci et c'est d'ailleurs ce que nous observons. Cela interdit l'utilisation d'un balayage sinus à vitesse lente car la contraction musculaire de l'animal, c'est-à-dire son état mécanique, varierait au cours de la mesure. Nous cherchons en effet les charactéristiques mécaniques du système dans un état constant. Une excitation simulanée à toutes les fréquences, précise mieux l'état du système.

4 - Enfin, le choix d'une excitation en bande de bruit nous semble une approche réaliste de l'environnement vibratoire mécanique de l'homme.

DR. J. CLEMENT (BE)

Comment expliquer la chute de votre fonction de cohérence aux fréquences basses?

AUTHOR'S REPLY

Une chute de la valeur de la fonction de cohérence étant observée, qu'il y ait (fig. 12) ou non (fig. 11) un animal sur la table vibrante, montre qu'il ne s'agit pas d'un "problème biologique".

En basse fréquence, les accélérations obtenues sont faibles. Il en est donc de même pour les forces. Le rapport signal sur bruit des mesures étant mauvais, la cohérence chute.

En très basse fréquence on pourrait remplacer la mesure de l'accélération par celle du déplacement.

A METHOD FOR STUDYING HUMAN BIODYNAMIC RESPONSES TO WHOLE-BODY Z-AXIS VIBRATION

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SUMMARY

This paper describes the methodology used and presents some illustrative results obtained in current experiments to determine the transmissibility of mechanical vibration to major axial segments (pelvis, upper torso, head) of the seated human body vibrated in the z-axis. Factors influencing transmissibility are mentioned and the importance of controlling such factors in experimental determinations of the human biodynamic response to vibration is discussed. The methodology described, adapted from established use in human impact studies, includes the use of standardized anatomical coordinate systems for data reference, which is essential to the meaningful comparison of responses measured in different subjects or in different conditions of vibration.

INTRODUCTION

In the proper study of the biomedical and psychological correlates of the human inertial response to force and motion inputs, it is necessary to make precise and repeatable determinations of the inertial response of body segments of interest and, for comparative analytical purposes, it is essential to be able to relate the segmental motion to clearly defined and preferably standardized anatomical coordinate systems (1, 2). Yet perusal of the published literature on human response to mechanical vibration or impact shows that the use of man-mounted inertial instrumentation in such a manner that meaningful and repeatable observations of skeletal motion can be reliably made, and related to a precise inertial frame of reference, has rarely been attempted and even more rarely achieved. As a rule, previous investigators, particularly of the human response to whole-body vibration (3), have satisfied themselves with estimates of the distribution of mechanical force or motion within the living body, based upon acceleration or displacement measurements made at the subject's seat, or have drawn conclusions - perilously subject to experimental error and artifact - from data yielded by instrumentation attached to arbitrary points on the body surface (sometimes located on soft tissue areas of undetermined dynamic characteristics). Such measurements have not, as a rule, been related to any properly defined anatomical coordinate system.

Using a man-mounted inertial instrumentation array and data reduction techniques already developed and proven for impact research at our laboratory (4), a series of experiments is underway to determine the seat-to subject and point-to-point (intersegmental) acceleration transmissibility of low-frequency whole-body vibration in man. This interim report describes approaches to the methodological standardization of certain aspects of human vibration experimentation, including the manner in which vibration is applied to the subject; the control of certain biodynamic factors (such as the subject's sitting posture) that can modify measured vibration transmissibility; and the acquisition and normalization of data obtained from vibrated living subjects for the purposes of comparative analysis between different exposure conditions, different subjects, and different species (5) used as human analogues in vibration and impact research.

METHODS

The subjects currently used in this program are young Navy enlisted men who have been medically qualified specifically (6) for participation in biodynamic experiments. The use of these volunteer human subjects is in accordance with SECNAV Instruction 3900.39A. Every subject is equipped with individually molded instrumentation mounts designed (4) to fasten rigidly 3-dimensional accelerometer arrays externally to the bony anatomy at the pelvis, the first thoracic vertebra (T_1) and the upper jaw. An additional mount carrying rate gyroscopes is fixed over the calvarium. The pelvic mount, formed by two half-rings located upon the bony prominences of the subject's pelvis, also serves as part of the restraint system used to secure the subject to the vibrating seat.

The use of these instrumentation mounts permits the instrumentation to be precisely and repeatably located with respect to the subject's bony anatomy during every run; and the precise and repeatable location and orientation of the functional elements of the transducers with respect to defined anatomical landmarks (previously determined for every subject by three dimensional x-ray anthropometry) permits the computational transformation of inertial data to points of interest defined in the respective anatomical coordinate systems, provided that the bony anatomy of each instrumented body segment can be shown to obey the laws of rigid-body mechanics (7).

Vibration conditions. Vertical sinusoidal (z-axis) vibration is applied to the buttocks and feet of the seated subject by means of a rigid seat (the top of which is shaped like an agricultural tractor driver's seat in order to locate the buttocks over the line of thrust of the vibration machine, currently, a 28,000 lbf electrodynamic device). The subject's feet are supported by a rigid footplate moving in phase with the seat. During vibration exposures, the subject is constrained to the seat and his posture is adjusted in a standard manner described below. His hands normally rest in his lap, and in his preferred hand he holds a switch which he is instructed to release in the event that he wishes to abort the run at any time (the medical officer in charge of the run can also abort the run at any time at his discretion by means of a separate, positive action switch).

In order to determine the linearity of the human inertial response as a function of input vibration force, measurements of transmissibility are being made at various acceleration-amplitudes up to and including the "Exposure Limit" defined in Reference (9) at selected frequencies of sinusoidal vibration within the band 2 to 32 Hz, and also during exposures to upgoing and downgoing frequency sweeps, mentioned in more detail below. Current exposure durations are 3 minutes for steady-state sinusoidal vibration and approximately one minute for sweeps. In addition to the man-mounted inertial instrumentation, reference accelerometers are mounted rigidly on the seat, the substructure of which also incorporates load cells for the purpose of determining the whole-body mechanical input impedance (not reported in this communication) simultaneously with transmissibility determinations, for comparative analysis.

Standardizing vibration exposures. The subject's buttocks are constrained to move with the vibrating seat by four separately buckled relatively inelastic straps running approximately vertically from the pelvic mount to the seat frame. Tensioning the straps augments the compression of the subject's bottom due to gravity. In some experimental runs, a lap-bar, approximately 10 cm in diameter, lodged between the anterior aspects of the pelvis and the subject's upper thighs when flexed in sitting, has been used as an alternate form of restraint that has proved more comfortable than the pelvic mount for long runs: this device, however, is not a suitable base for inertial instrumentation. In both methods, the tie-down straps carry strain gauges whose outputs can be monitored for the purpose of adjusting the tie-down to a standard tension for all runs. However, the effect of varying the strap tension on measured transmissibility, and the optimal tension for general experimental purposes, have yet to be determined: it has proved very difficult in practice to achieve even or repeatable strap tensions, either as initial conditions or during runs, due to the subject's ability to reposition himself; and we are not yet convinced that to do so is a necessary or desirable objective, which is the reason for use of the pelvic mount.

The subject's sitting posture, a variable known to affect transmissibility determinations markedly (3) is adjusted at the outset of every run in which inertial data are to be collected, and from time to time during the run, by having the subject maintain an image of his own instrumented head (right lateral view) within a template marked for that individual on the screen of a television display in front of him. The display is generated by a television monitoring camera mounted approximately 2 m to the side of the subject's head. This device, developed originally to control the initial conditions in human impact experiments (8), has proved to be a simple and effective way to standardize and control the subject's posture and degree of volitional muscular effort during vibration.

DATA ACQUISITION AND ANALYSIS

The inertial data measured by the seat reference and man-mounted transducers are (in addition to being displayed graphically in real time for monitoring purposes) recorded initially on analog magnetic tape against a universal time base. The data are later converted to digital form for acceptance by computer programs previously developed in our laboratory for human and subhuman primate impact and vibration studies. Formal analysis of the data begins by digitizing each of the recorded transducer signals at 300 samples per second (equivalent to a minimum of 10 samples per cycle of vibration up to 30 Hz) and transcribing the values onto digital tape. A computer program analyzes calibration signals for every run to determine the correct scaling information for each channel of data. The resultant digital data are then converted to engineering units and passed through digital filters to remove unwanted signal components (e.g. 60 Hz electrical noise and d.c. bias). Using the geometric relationships between the functional orientation and location of the transducers and the subject's bony anatomy, as determined individually by 3-dimensional x-ray anthropometry, the 3-dimensional motions at specific points of the anatomy are computed. Figure 1 illustrates this process. The three anatomical points used to represent segmental body motions in the experiment illustrated below were the nominal center of gravity of the head, the anterior superior corner of the T_1 vertebral body in the midsagittal plane, and an external point related to the anatomical coordinate system for the pelvis (1, 2, 4). All instrumentation is positioned in or near to the midsagittal plane, to take advantage of the presumed lateral symmetry of the subject's response.

Some results obtained. Some experiments have been made in which the frequency is steadily varied, at a rate of 0.5 Hz per second, over the spectrum of interest. Such an approach affords certain advantages with regard to experimental and analytical economy. The mathematical procedures developed for swept-sinusoidal vibration response analysis, using primate data, have been reported previously (5). In the current human studies, the linear acceleration (in three orthogonal axes), the angular acceleration and the angular velocity are calculated for each of the anatomical points mentioned above. The data shown in Figure 1 are a 5-second segment from a 54-second test in which the vibration frequency was swept from 5 to 32 Hz. The excitation frequency was 5 Hz at the start of the segment illustrated, which shows aspects of the segment-to-segment propagation of vertical input vibration up the seated body in one subject.

The response of the head to whole-body vertical vibration at low frequencies is a characteristic nodding motion in the sagittal plane; lateral vibration is negligible, and rotational oscillation occurs only about the head y-axis. The data transformed to the T_1 coordinate system indicate a response similar to that of the head; however, two compromising factors must be noted. The instrumentation mount at T_1 is attached to the torso by straps which (as can be confirmed by means of high-speed cinephotography) can permit a slight rocking motion about the instrumentation point under the vibration stimulus; therefore, some error may be expected in the measured values for motions in the z-axis and about the y-axis for T_1. Scrutiny of the T_1 data in figure 1 indicates that these signals do indeed appear distorted, presumably because of imperfection in the fastening of the T_1 instrumentation mount to the torso in that run. Moreover, during these preliminary experiments, a complete instrumentation package was not yet available for T_1; consequently, it was necessary to use the presumed symmetry of motion with respect to the sagittal plane to transform the data to the reference point in T_1. Errors introduced by that assumption of absolute lateral symmetry result in slow drifts in the baseline for T_1 angular velocity (derived by integration of acceleration signals) about the T_1 y-axis.

The data recorded from the pelvic mount have not yet been precisely defined in relation to the subject's bony anatomy. This is because the efficacy of various arrangements of pelvic instrumentation and restraint is still being evaluated and therefore x-ray anthropometry of the region would be premature, and not justified. Furthermore, we do not yet have a

complete instrumentation package for the pelvis. Provisionally, it may be said that the vector sum (not shown) of the x-, y-, and z-axis linear acceleration is approximately equal to the vertical acceleration at the pelvis. The rotational data from the pelvis, however, may contain a component of error undeterminable because of the incomplete instrumentation array; these data should accordingly be disregarded for the purposes of this presentation.

Results of supplementary analyses. The format used for presenting data in Figure 1 has several deficiencies. First, it is inefficient, showing only a short segment of data from a sweep. Second, it does not define relationships (transmissibilities) between different body segments. Moreover, although the vibration frequency is steadily changing during the sweep, its instantaneous value is not readily ascertainable from figure 1. For these reasons, an alternative method of presenting the data has been developed, in which a computer program has been designed to scan the data for each channel, calculate specific parameters which describe the data and their relationships to corresponding data in other channels, and display the results graphically. Figure 2 shows the rms amplitude of the seat z-axis acceleration as a function of vibration frequency swept from 5 to 30 Hz. The rms amplitude is calculated by using an exponential smoothing technique in which the data closest to the point of interest are weighted most heavily in the computation of the rms value. In the run illustrated in Figure 2, the seat rms vertical acceleration began at 0.7 m/s^2 and gradually decreased to 0.2 m/s^2. Because it is possible that directional artifacts may occur in the implementation and analysis of swept-sinusoidal vibration tests, a check was made by repeating the experiment but sweeping in the opposite direction, viz, from 30 down to 5 Hz. The rms computation for that test is shown in Figure 3. Comparison of the data from Figures 2 and 3 showed approximately 0.01 m/s^2 bias in the two procedures. While this is quite small, work is in hand to modify the analysis algorithms to remove most of that bias.

Figure 4 shows the rms amplitude of the head z-axis acceleration, and Figure 5 shows the comparison (in effect, a determination of transmissibility) or ratio between the head z-axis and the seat z-axis accelerations. It is immediately apparent that a resonance occurred in the body somewhat below 6 Hz. This is in general accord with previously published work using human whole-body mechanical impedance and transmissibility methods (3). Characteristically, the transmissibility is less than unity at frequencies above 10 Hz. Figure 6 shows the phase relationship between the two signals; again, a phase lag of some 90° at and above resonance is characteristic. Figure 7 shows the cross-correlation between the same two signals (this parameter is especially powerful if the input signal approximates a sinusoid). For sinusoidal inputs, a correlation of unity is strongly indicative of a linear relationship between the input and output signals, whereas correlations below about 0.75 indicate either that the input signal was not sinusoidal or that the system is nonlinear. From Figure 7 it appears that a linear relationship may exist between the two signals up to some 17 Hz at the acceleration amplitudes investigated. Above some 17 Hz, the subject may effectively isolate his head from the transmitted vibration (which at high frequencies is of progressively lessening displacement-amplitude). Figure 8 confirms the stable relationship between the excitation frequency, as determined from the seat reference accelerometer output, and elapsed time, i.e., that the sweep rate was steady at approximately 0.5 Hz. All the calculations required for the analysis of the data, and the construction of the plots shown in Figures 2 to 8 were done by computer.

Work in progress. To date some 80 human runs have been completed as part of a series intended to cover the frequency band 5 to 32 Hz (later frequencies below 5 Hz will be included, using an electrohydraulic vibration machine being brought into service for human experimentation) at three acceleration levels for our available range of subject percentiles. So far, for vibration exposures not exceeding the ISO "Exposure Limit" for short durations (9), the methods of instrumentation, control of the subjects' posture, and constraint of the subject to move with the seat, have caused no serious problems. In the course of the current series of transmissibility determinations, the same subjects are simultaneously carrying out tests of visual resolution acuity using Landolt C test material, and giving subjective ratings of vibration severity on a 9-point scale. Data from these tests are as yet too few for definitive statistical analysis, which will be carried out and reported separately when the series of runs has been completed by all subjects in all conditions.

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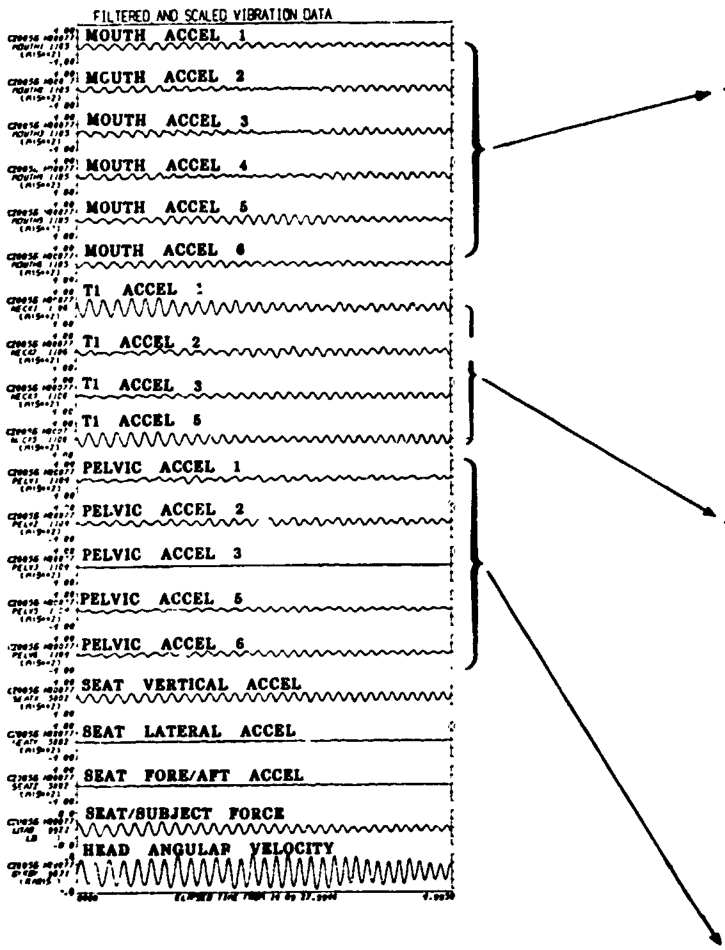
Opinions and conclusions contained in this report are those of the authors and do not necessarily reflect the views or endorsement of the Navy Department.



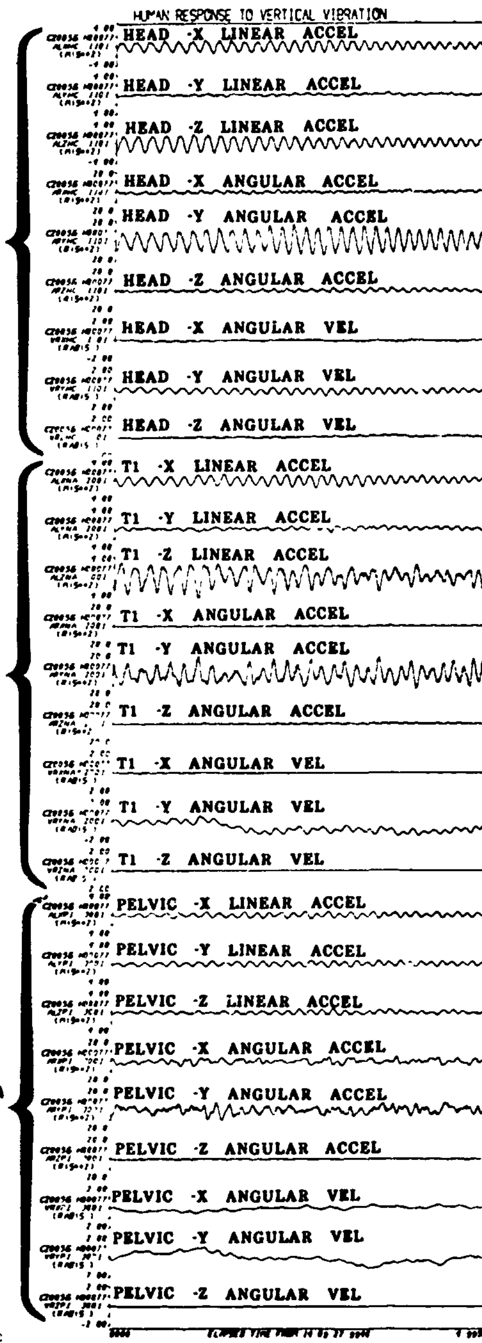


FIGURE 1. Data reduction process. The right-hand panel shows the human response to vertical seat vibration yielded by geometric transformation from the filtered and scaled vibration data shown in the left-hand panel. The sample length is 4.995 seconds in each panel. The data are from the first 5 seconds of an upgoing frequency sweep beginning at 5 Hz, at a seat vertical (z-axis) acceleration-amplitude of 0.7 ms^{-2} rms. The transformations are a mathematical operation based upon calibrated radiographs showing the precise location of the instrumentation with respect to bony landmarks in each subject.

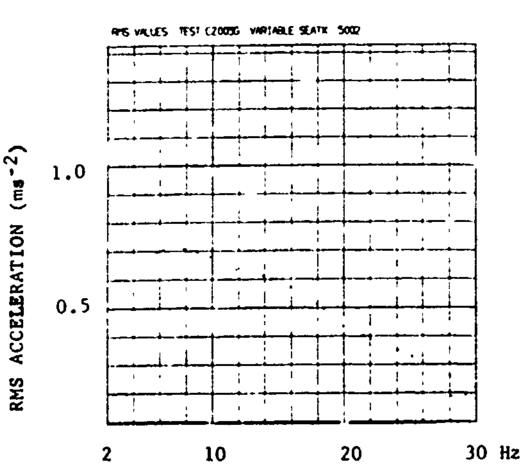


FIGURE 2. Seat z-axis rms acceleration in meters/second/second as a function of vibration frequency (sweep from 5 to 30 Hz).

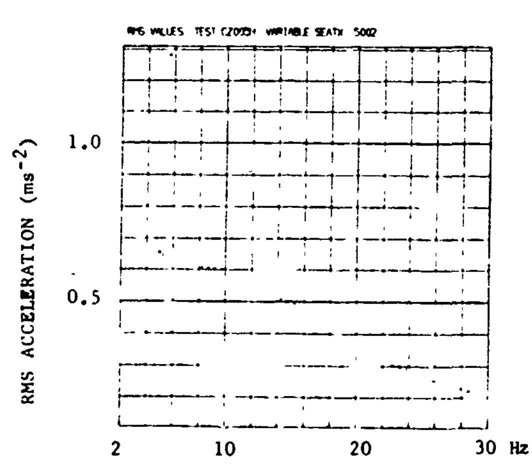


FIGURE 3. Seat z-axis rms acceleration (ms^{-2}) as a function of vibration frequency (sweep from 30 to 5 Hz).

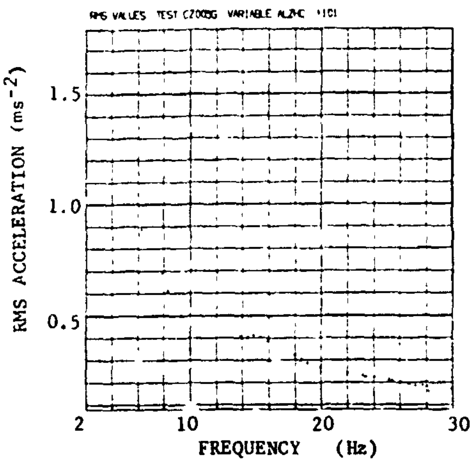


FIGURE 4. Head z-axis rms acceleration (ms^{-2}) from 5 to 30 Hz. (The data have been transformed to the coordinate system for the head.)

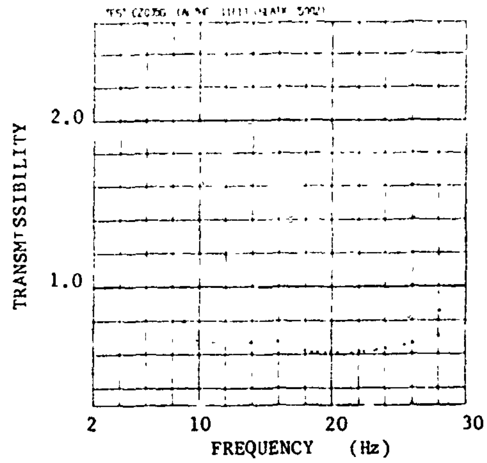


FIGURE 5. Transmissibility of seat z-axis acceleration to the head z-axis. Transmissibility exceeding 1.0 in the region of 6 Hz indicates an axial body resonance occurring between seat and head.

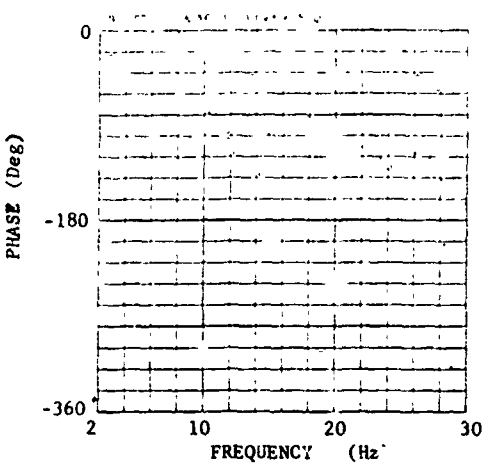


FIGURE 6. Phase lag of head z-axis acceleration with respect to the seat z-axis acceleration.

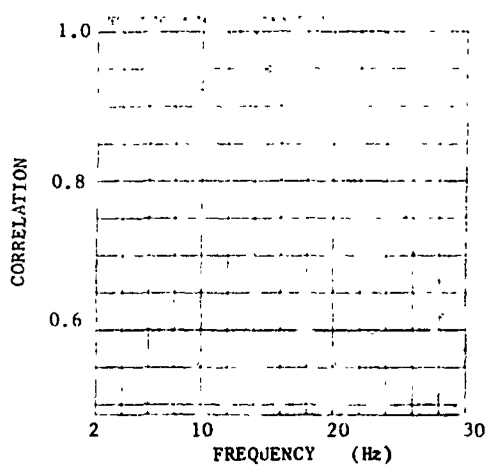


FIGURE 7. Cross-correlation between head z-axis acceleration and seat z-axis acceleration.

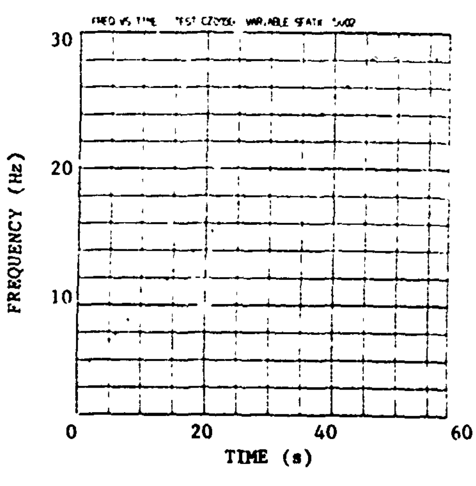


FIGURE 8. Relationship between vibration frequency and time during upgoing sweep from 5 to 30 Hz.

DISCUSSION

DR. P.J. THOMAS (US)

To what extent does coupling of the man (pelvis to shaker), and the inherent complexity of the transmissibility matrix, affect efforts to describe a standardised human response?

AUTHOR'S REPLY

When a standard attempts to prescribe limiting whole-body impacts (as does ISO 2631:1978, for example), allowance must of course be made for any resilient coupling, such as a seat cushion, between the point of measurement and the point of input to the man. Any standard purporting to describe or define a human mechanical characteristic, such as whole-body input impedance, or seat-head transmissibility, must recognise the fact that measurements may be affected by both intrinsic (for example, degree of compression of tissue of the buttocks) and extrinsic (for example, degree of body loading by a restraint system) biodynamic factors. If the pelvis, ideally, is taken as the input point for two-axis whole-body vibration (rather than the man-seat interface), when drawing up a standard for transmissibility of vibration to the head, then the resilience or coupling between pelvis and seat may be immaterial. External loadings, posture and so on, however, would still be controlling factors.

HEAD MOVEMENTS INDUCED BY VERTICAL VIBRATIONS

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SUMMARY

Vibration transmission through the human body from seat to head under vertical (z-axis) vibration has been investigated in the past by taking into account only the vertical head movements. To assess the complex head motion induced by z-axis mechanical vibration, eleven subjects were vibrated on a shake-table in the frequency range of 2 Hz to 19 Hz. Acceleration amplitude was sinusoidal and held constant at 0.35 g (rms). Each subject was given two trials: one sitting relaxed without a backrest, the other leaning against a backrest with a 12° inclination from the vertical. Head motion was recorded with a special television camera (x-y tracker) by pursuing a target painted on the temporal part of the subject's forehead. This instrument continuously records the horizontal and vertical co-ordinates of the tracked point and gives the output as analogues voltages. For each frequency and experimental condition the vertical and horizontal motion of the tracking target was related to the displacement of the shake-table.

The results are given as different transmissibility curves for vertical and horizontal head motion. When relating horizontal to vertical transmissibility it becomes obvious that, without a backrest, at the resonant frequency the horizontal transmissibility is about 75 % of the vertical transmissibility.When using a backrest horizontal transmissibility is reduced to about 35 % of the vertical transmissibility.

INTRODUCTION

Vibration transmissibility has been widely used in the past to describe the response of the human body to mechanical vibration. Transmissibility is defined as "The nondimensional ratio of the response amplitude of a system in steady-state forced vibration to the excitation amplitude. The ratio may be one of forces, displacements, velocities, or accelerations" [1].

$$\text{Transmissibility}\ (\omega) = \frac{\text{output}\ (\omega)}{\text{input}\ (\omega)}$$

In the laboratory, transmissibility is usually determined by placing one accelerometer on the shake-table and a second on that portion of the body whose transmissibility is to be recorded. For each tested frequency, the complex ratio of the two accelerations is formed and plotted versus frequency.

Vibration transmission from seat to head is considered most vital by many authors. This is obvious because the head serves as a stabilizating platform for the eyes, the most important sensory organ for flight. Although many vibration problems have faded away with the overall use of jet propulsion and modern aircraft design, there are still areas in military aviation which pose problems induced by mechanical vibration. One is high-speed, low-level flight, while others are related to helicopter operations.

Mechanical vibrations can influence comfort, performance, and health of human beings. In aviation, performance of aircrews is often adversely affected by visual disturbances evoked through mechanical vibrations. Blurring of the visual image on the retina, caused by relative movements between the eye and the viewed object, is the most apparent cause of visual problems during vibration. The effects of mechanical vibration on vision have been reviewed among others by Shoenberger [13] and recently by May [9]. While May summarizes his review with the general statement that disturbance of vision by vibration is proportional to frequency and input amplitude, Shoenberger gives a more refined résumé: "In summary, when vertical, whole-body vibration is applied to a man in upright seated position, there are primarily three frequency related factors that appear to have a bearing on visual decrements. These are: compensatory tracking movements of the eye at very low frequencies, amplification or attenuation of vibration from seat to head (including rotation and resonance of the head itself), and resonance associated with the eyeball and/or its supporting structures at high frequencies."

Different approaches have been made in aviation research to overcome the visual problems associated with mechanical vibration in high-speed, low-level flight. One is to reduce turbulence-induced aircraft movements by aerodynamic control surfaces which are automatically activated by a closed control loop. Another approach is to move the visual

target for the pilot in phase and amplitude with head motion and thus stabilize the image on the retina. The latter method requires a good knowledge of the response of the human body to vibration.

While whole body mechanical driving point impedance is an indication for the overall response of the human body to mechanical forces, transmissibility measurements can identify the reactions of special body parts.

Already in 1939 v. Bekésy [2] described the damping of vibrations by the body, however, without observing any resonances.

Dieckmann [6] investigated the dynamic behaviour of the human body in 1957, and found the main body resonances between 4 and 5.5 Hz. He explored vibration transmissibility from a vibrating platform to the hip, shoulder, and head. Coermann [4] measured transmissibility from a seat to head of subjects in erect and relaxed sitting postures. He described a reduction in head amplitude with a concomitant shift of the main resonance frequency from 4 Hz to 5 Hz as the subjects changed their posture from sitting relaxed to sitting erect. The latter posture also resulted in a reduction of peak head amplitudes. Coermann and Okada [5] investigated the effect of a backrest and seat-back angles between 90° and 140° from the horizontal on vibration transmission to the head. The results showed that a back-angle of 140° produced the lowest transmissibility magnitude while 100° produced a maximum head amplitude at whole body resonance. Vibration transmissibility to the head under various levels of sustained acceleration has been measured by Mertens [10]. His results show an increase of head amplitude between +2 G_z and +3 G_z and a whole body resonance at approximately 10 Hz under +3 G_z sustained acceleration. The influence of body posture on vibration transmission to the head was investigated by Griffin et al. [8] for a wide variety of postures, subjects, and input functions. Posture and seat configuration played the major role in transmissibility while other variables had only minor influences. This influence of seat design and body posture has been likely found by Bjurvald et al. [3] and Rowlands [11]. The transmissibility magnitudes from these investigations are shown together in Figure 1.

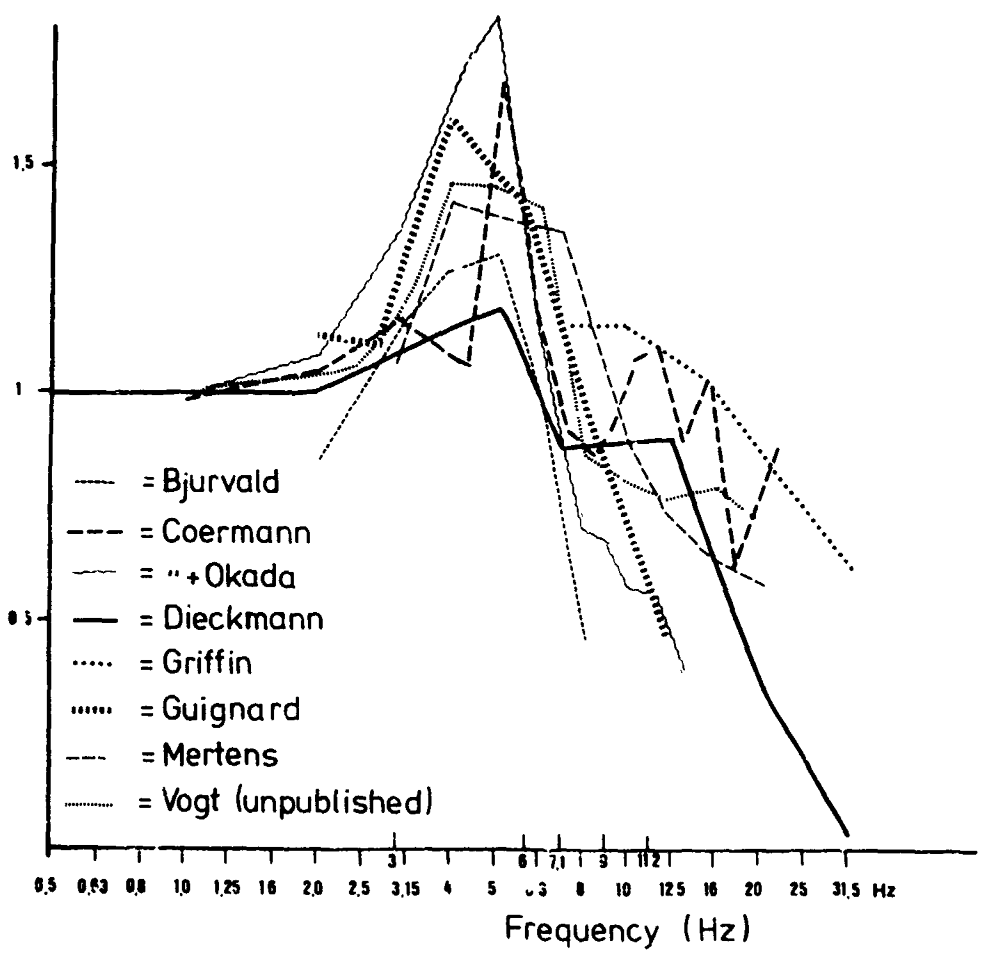

Figure 1: Vibration transmissibility seat/head for sitting subjects.

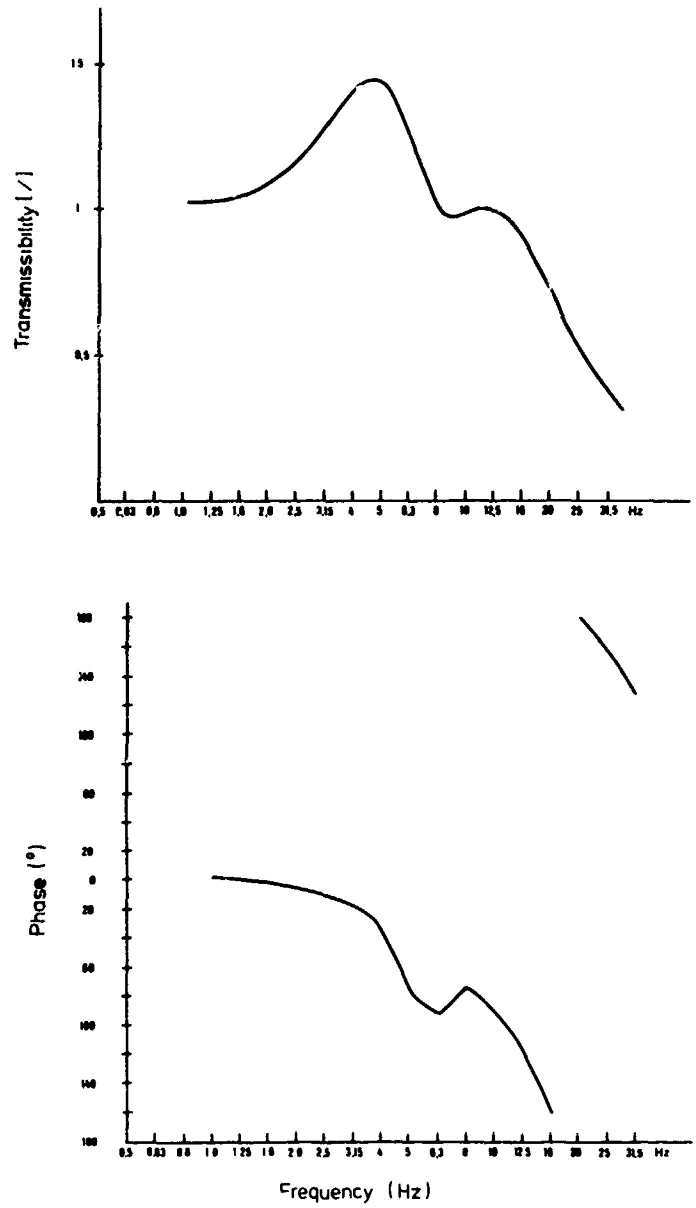

Figure 2: Proposed standard transmissibility curve.

While the first resonance at 4.5 Hz is clearly evident in nearly all curves, their courses differ considerably after the first maximum. This is caused by different measurement techniques and body posture. In spite of that, an attempt was made by Working Group 5 of ISO TC 108/SC 4 to propose a standard transmissibility curve, shown in Figure 2, for magnitude and phase.

Most of the authors quoted employed accelerometers fastened to the head either by a bite-bar or by some other means such as straps or even helmets. For calculating transmissibility they used only the vertical (z-axis) component of head vibration. It is well known, and may easily be observed in the laboratory, that the head also moves in the horizontal direction even when the vibration excitation of the body is strictly vertical. Sandover [2] compared vibration transmission measured with a bite-bar accelerometer and an accelerometer mounted on the top of a lightweight head harness; the results differ in resonant frequency and amplitude. The author emphasizes the dangers of not allowing for the obvious effects of complex movements. Dieckmann [7] recorded complex head movements induced by horizontal (x-axis) mechanical vibrations and found considerable, vertical displacements of the head. Figure 3 gives the elliptic movement of the head calculated from horizontal and vertical acceleration components and their phase relationship.

The purpose of this paper is to present data of complex head movements induced by vertical (z-axis) vibrations of sitting subjects.

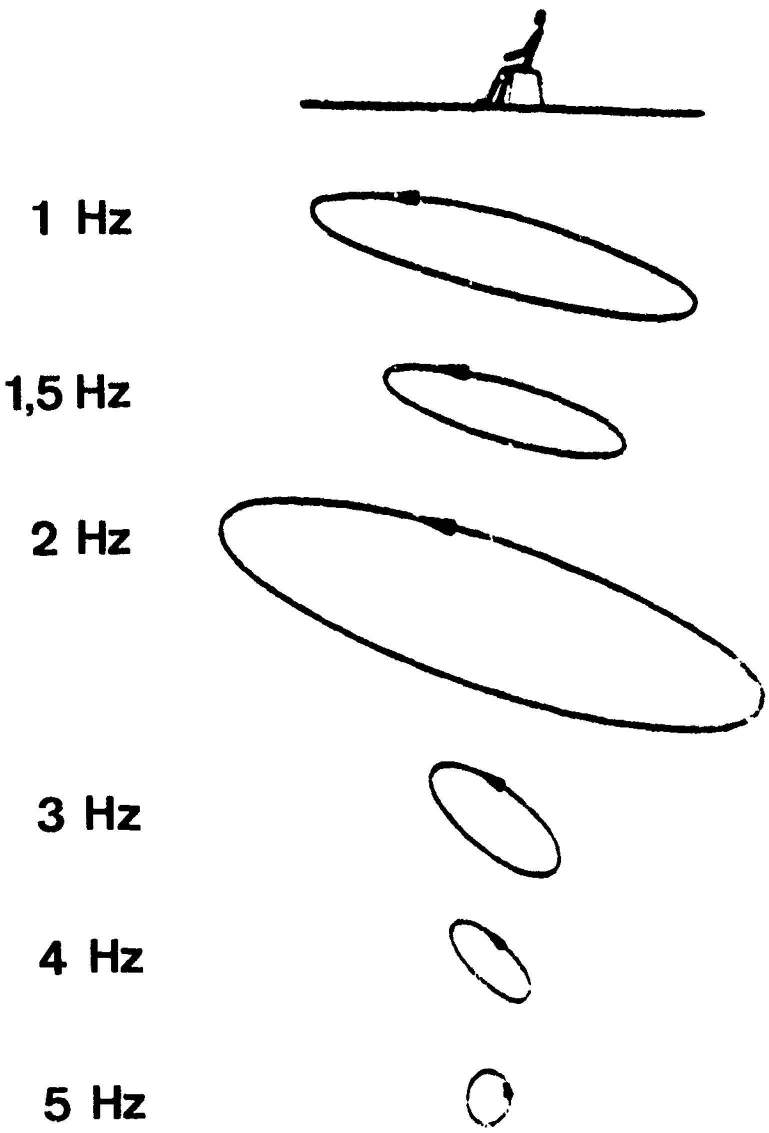

Figure 3: Complex head motions of a sitting subject under x-axis horizontal vibration (after Dieckmann [7])

METHOD

Eleven healthy, male subjects were used for this investigation; their age, height and body weight are given in Table I.

All subjects were volunteers from our laboratory staff. Each subject underwent two trials on the shake-table, the first with a backrest which had an inclination of 12° to the rear from the vertical. The second experiment was without backrest. The subjects were instructed to maintain a relaxed posture in both cases. An electro-hydraulic shaker produced sinusoidal vibrations in the frequency range of 2 to 19 Hz in one Hertz increments. Acceleration amplitude was kept constant at 0.35 g (rms).

The schematic data acquisition system is shown in Figure 4. The temporal region of the subjects' head was painted black with theatrical make-up to create an even, dark background; upon this, two dots were applied with white paint, two centimeters apart, which presented the tracking targets for the x-y tracker. A stencil was used to obtain a uniform placement of targets. During the experiments, the foremost point was always tracked while the other one was only used for calibration purposes.

The tracking of the target mark was accomplished with a multipoint x-y tracker (HTV-C 681, Manufacturer: Hamamatsu TV Co., Japan) consisting of a TV camera using the electrostatic type of image dissector tube. The camera with the associated electronics is able to pick up three points simultaneously and give the x and y co-ordinates of

Table I:

Subject No.	Age (Years)	Height (cm)	Weight (kg)
1	33	183	65
2	47	176	82
3	40	181	85.5
4	42	172	75
5	29	180	67
6	37	178	74
7	34	175	63
8	28	184	85
9	27	178	80
10	38	173	64.5
11	46	172	63

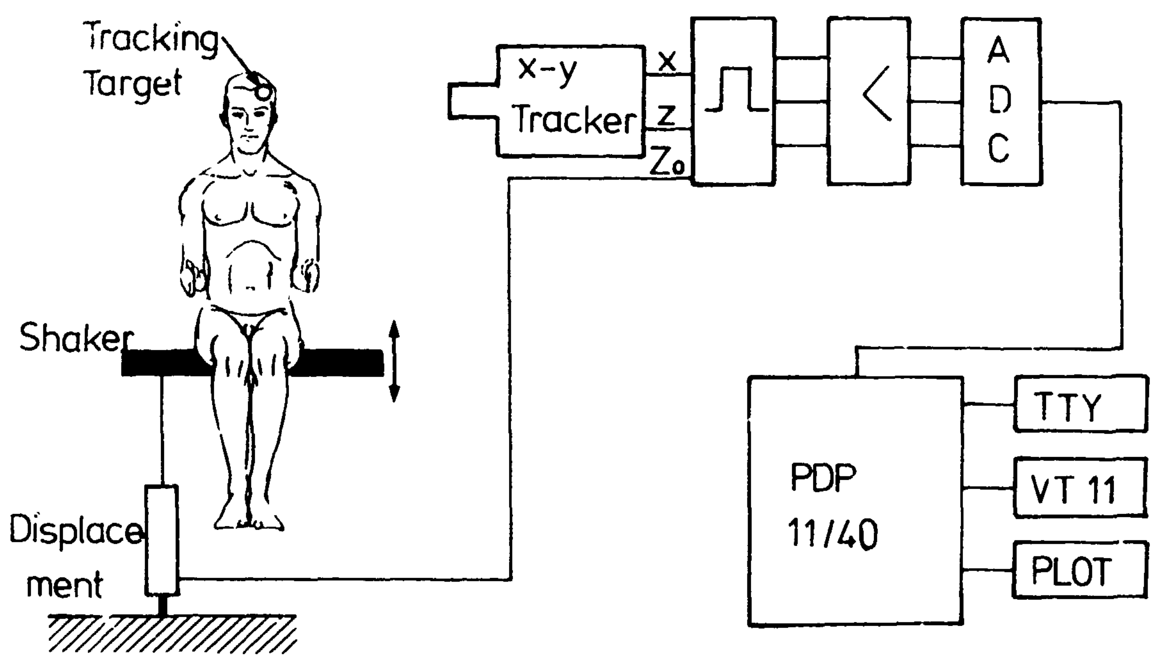

Figure 4: Schematic for the data acquisition system and vibration stand employed in the determination of head motion.

these points as analogue voltage outputs. The sampling rate of the camera for three points is 5.25 kHz; the accuracy is better than ± 2 % of full scale. The resolution of the system cannot be stated exactly, since it depends on the focal length of the lens used, and the distance between camera and object. We circumvented this problem by monitoring the output of the x-y tracker on an oscilloscope together with the displacement signal of the shaker taking care that a good signal to noise ratio was maintained. The data were again checked on the computer display before processing.

All signals were sent through band-pass filters of the same design which were tested for equal phase and amplitude characteristics. The high-pass part of the filter had a cutoff frequency of 0.5 Hz and the low-pass of 250 Hz. It was used as an anti-aliasing filter for the analog to digital converter (ADC), while the high-pass compensated for the slow movements of body sway during the test-runs without backrest. The filters had a rolloff of 20 dB/octave. The sampling rate of the ADC was 512 samples per second. The data were digitized and stored on a magnetic disk using a PDP 11/40 computer. Data were then checked visually on a graphic display (VT 11) and underwent a process of digital filtering. This was accomplished by a forward Fourier Transformation. From the results only the amplitudes and phase of the test-frequency and one each at the adjacent upper and lower frequency were taken, and then a reverse Fourier Transformation was made

RESULTS AND DISCUSSION

Figure 5 shows a typical plot of head movements, before digital filtering, for vibration frequencies of 2 to 19 Hz.

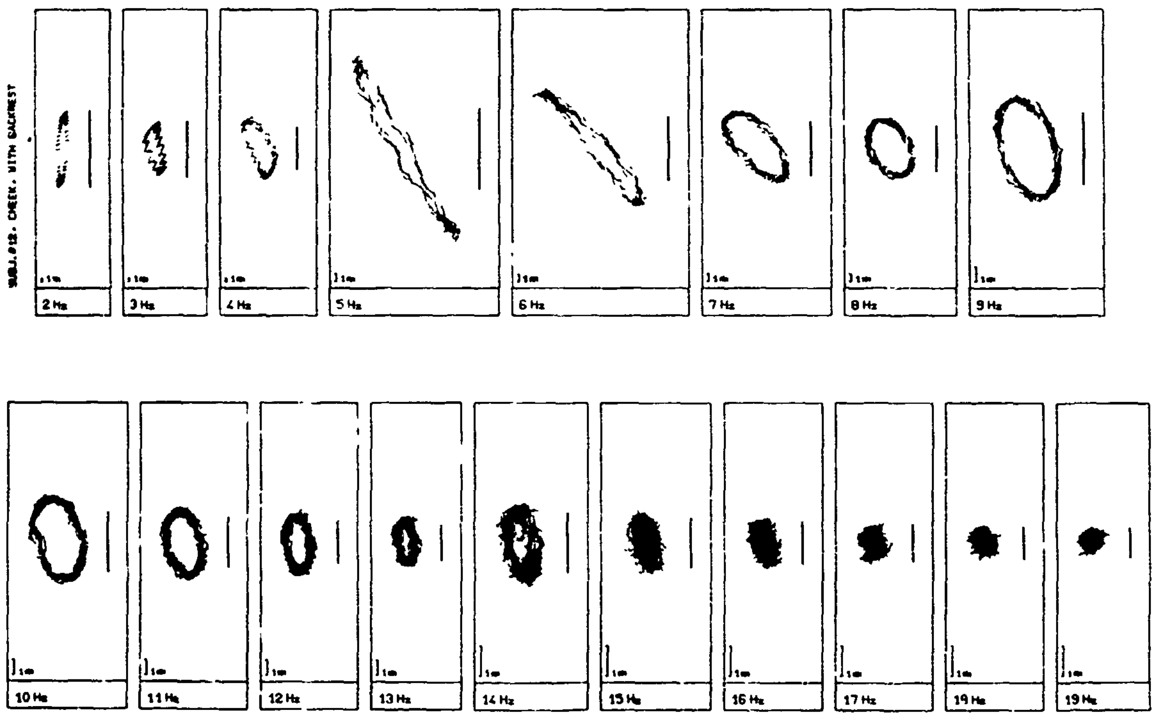

Figure 5: Complex head motion of one subject (unfiltered)

Together with the elliptical head motion, the shake-table displacement is given as a vertical line. In the lower left corner of each frame a calibration step of one millimeter is displayed. Because amplification was increased at 5 Hz by a factor of 2.5, at 9 Hz by a factor of 5, and at 14 Hz by a factor of 10, the calibration signals become larger at these respective frequencies. Data were sampled over a period of one second, and for this reason, the number of ellipses drawn in each frame equals the shaker frequency.

It is obvious that from 15 Hz upwards the ellipses become increasingly filled. This is due to a deterioration of signal to noise ratio because the absolute displacements become smaller with increasing frequency.

In the next two Figures (Figure 6, Figure 7), head motions of the same subject as in Figure 5 are shown after the data were filtered digitally on the computer. In addition, only one ellipse is drawn for each vibration frequency. In the upper half of the figures, the results of test runs with a 12° backrest are shown while the lower half displays results achieved without a backrest.

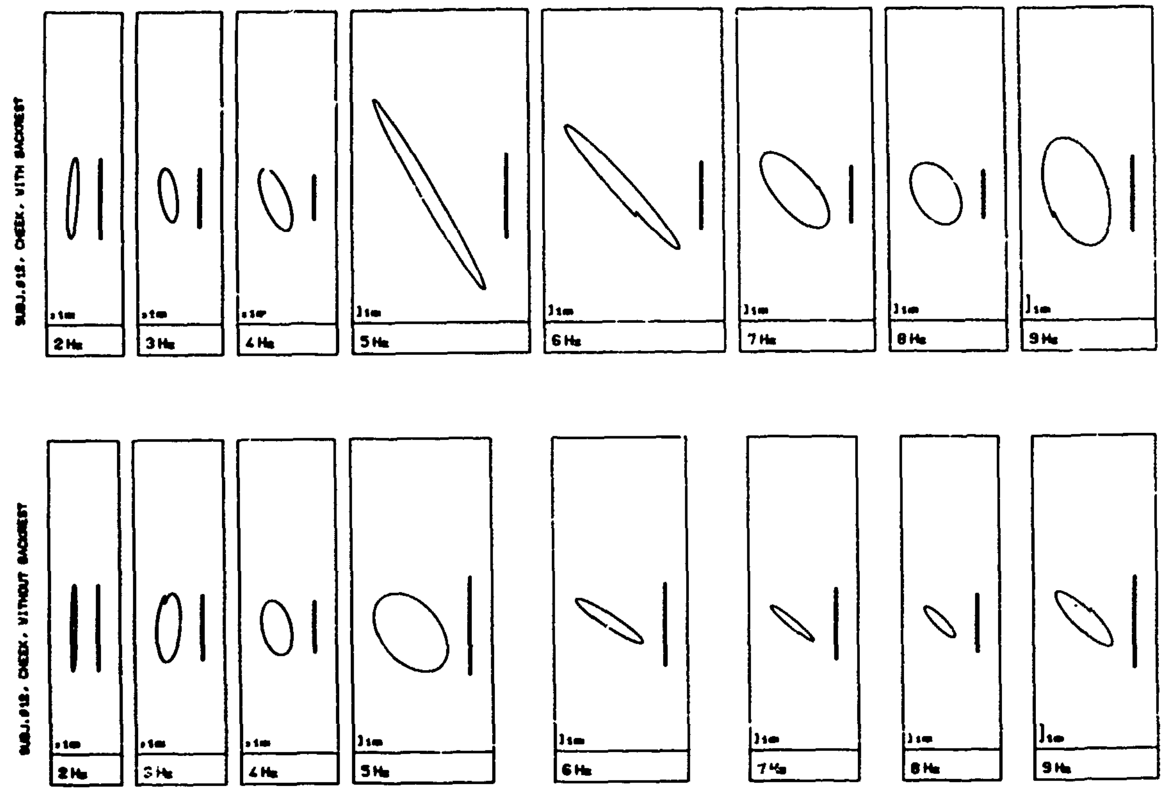

Figure 6: Complex head motion plotted from filtered data for the frequency range 2 Hz - 9 Hz. Upper: with backrest, lower: without backrest.

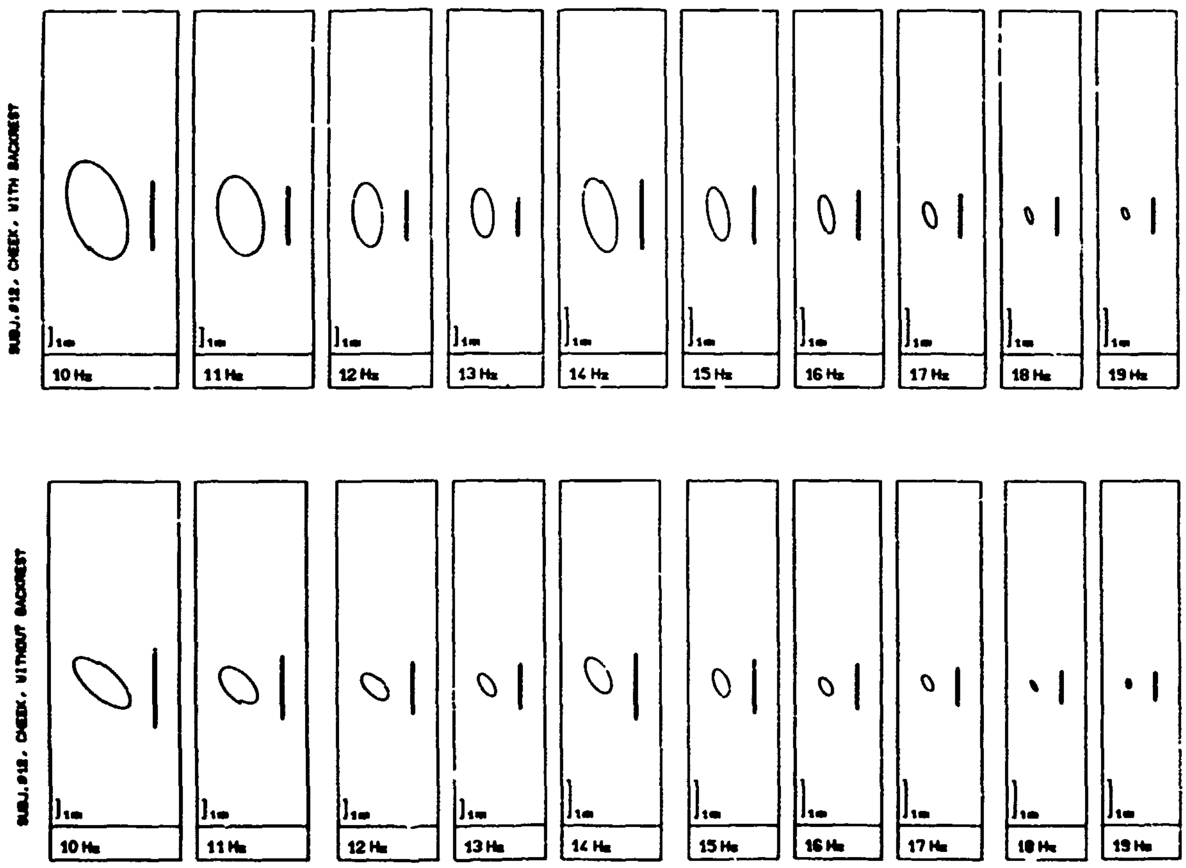

Figure 7: Complex head motion plotted from filtered data for the frequency range 10 Hz - 19 Hz. Upper: with backrest, lower: without backrest.

Looking at the upper part of Figures 6 and 7 first, it becomes obvious that from 4 Hz upwards, a considerable horizontal component of vibration is created by the human body especially in the region of whole body resonance around 5 Hz. This is indicated by a forward inclination of the long axis of the ellipse. After 10 Hz, this axis assumes a near vertical position again. Without backrest (lower part of Fig. 6 and 7), the maximum horizontal component, however, is - for this subject - located at 6 Hz.

In Figure 8, the transmissibility values of the same subject with backrest (a) and without backrest (b) have been calculated and plotted versus frequency. The dotted lines represent only the vertical component of head displacement related to shake-table displacement (vertical transmissibility). The solid lines represent the ratio of the horizontal component of head motion to table displacement (horizontal transmissibility). Although the phase curves given for the latter case do not have much meaning, since they describe the phase between two vibrations acting in directions perpendicular to each other, they are presented for further consideration. The vertical transmissibility curves (dotted lines) are in good agreement with published results for both test conditions (see Figure 1). They indicate the well-known first resonances at 4 Hz and 5 Hz and a second peak at approximately 10 Hz. As could already be presumed from the analogue presentation of head motion in Figures 5 - 7, the largest horizontal motion is also in this frequency range.

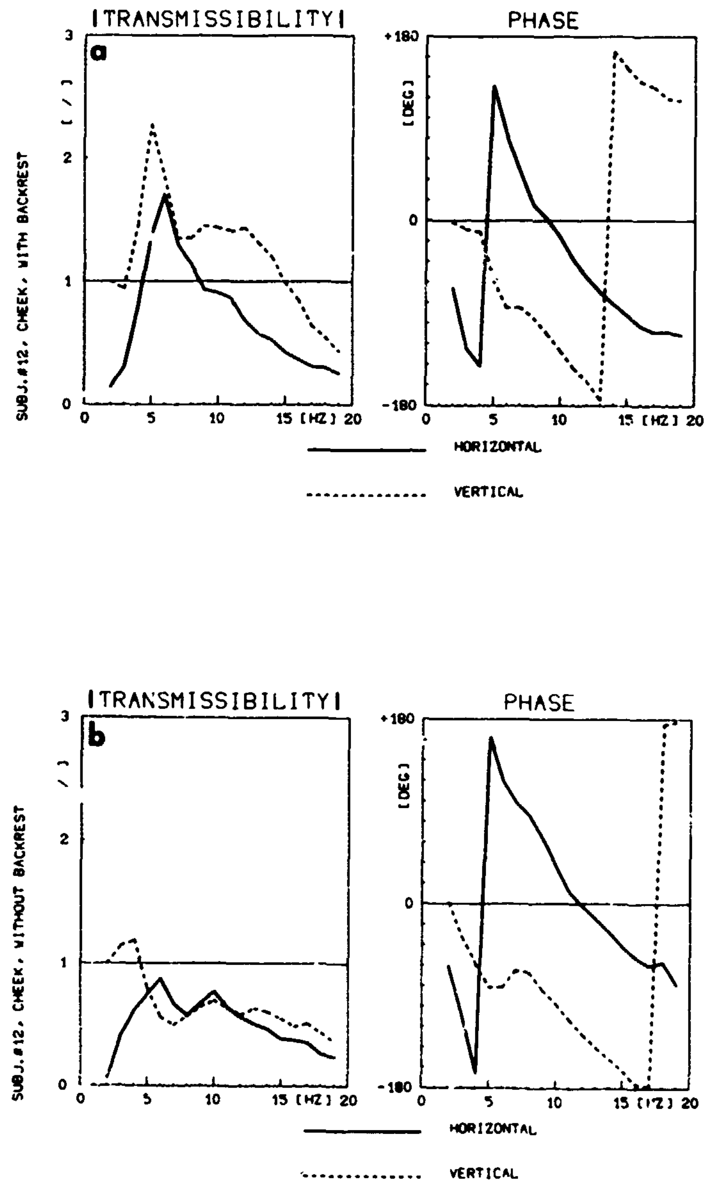

Figure 8: Vertical and horizontal transmissibility and phase for one subject:
a. with backrest,
b. without backrest.

Figure 9 together with Tables II and Tables III gives the mean values for 11 subjects with ±1standard deviation. For the phase curve in Figure 9c the results of only eight subjects were used and for Figure 9d only seven. This resulted from the fact that there are two characteristic types of phase curves for vertical transmissibility.

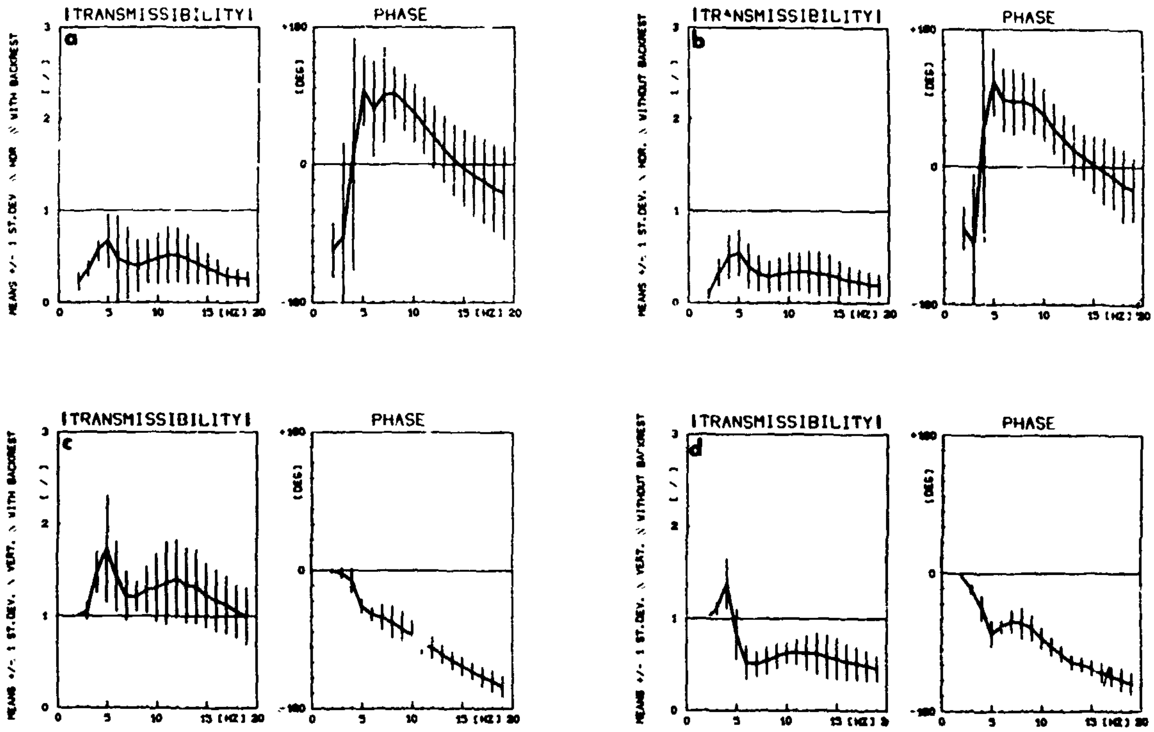

Figure 9: Mean values and standard deviation of horizontal and vertical transmissibility (N=11 (for phase see text)).
a. horizontal with backrest; b. horizontal without backrest;
c. vertical with backrest; d. vertical without backrest.

Table II: Means and standard deviations for transmissibility modulus and phase with backrest

	Vertical				Horizontal			
	Modulus [/]		Phase [°]		Modulus [/]		Phase [°]	
Frequ. (Hz)	Means	St.Dev.	Means	St.Dev.	Means	St.Dev.	Means	St.Dev.
2	1.00	0.00	0.1	2.5	0.23	0.10	-122.4	36.0
3	1.05	0.10	- 3.5	6.6	0.36	0.08	- 94.1	122.8
4	1.48	0.23	- 13.2	16.1	0.57	0.13	13.7	151.9
5	1.73	0.59	- 45.5	9.1	0.67	0.30	96.2	46.5
6	1.43	0.38	- 56.6	8.7	0.48	0.47	73.1	63.3
7	1.22	0.27	- 60.6	16.7	0.42	0.39	91.3	62.8
8	1.21	0.16	- 66.8	21.1	0.40	0.29	92.9	34.3
9	1.28	0.25	- 76.1	23.1	0.44	0.24	80.8	37.3
10	1.31	0.37	- 84.2	19.7	0.4[illegible]	0.28	66.7	38.3
11	1.35	0.45	- 93.4	15.3	0.51	0.31	50.4	37.4
12	1.41	0.43	-100.2	14.7	0.52	0.30	35.4	40.9
13	1.34	0.41	-108.9	12.0	0.47	0.28	20.3	43.9
14	1.32	0.41	-117.0	11.9	0.42	0.23	5.2	46.[illegible]
15	1.22	0.35	-124.4	12.1	0.36	0.17	- 4.6	50.5
16	1.17	0.34	-131.3	11.1	0.33	0.14	- 15.2	53.3
17	1.13	0.31	-138.2	13.2	0.28	0.11	- 22.2	55.3
18	1.05	0.29	-144.2	14.1	0.27	0.09	- 30.9	57.2
19	1.00	0.31	-151.3	13.9	0.25	0.08	- 37.4	61.0
N	11		8		11		11	

Table III: Means and standard deviations for transmissibility modulus and phase without backrest

	Vertical				Horizontal			
	Modulus [/]		Phase [°]		Modulus [/]		Phase [°]	
Frequ. (Hz)	Means	St.Dev.	Means	St.Dev.	Means	St.Dev.	Means	St.Dev.
2	1.00	0.00	- 2.9	1.9	0.10	0.06	- 81.2	28.6
3	1.11	0.07	- 21.1	6.1	0.33	0.15	- 99.8	89.4
4	1.38	0.27	- 44.8	16.9	0.51	0.24	50.8	148.7
5	0.83	0.28	- 78.6	17.5	0.55	0.25	111.8	44.7
6	0.53	0.19	- 69.1	8.6	0.40	0.24	87.9	41.5
7	0.51	0.14	- 62.5	14.7	0.33	0.20	84.9	43.5
8	0.54	0.15	- 64.9	20.2	0.29	0.17	86.3	37.9
9	0.60	0.14	- 71.4	17.0	0.31	0.18	79.6	37.5
10	0.62	0.11	- 84.3	14.0	0.34	0.21	67.2	36.6
11	0.54	0.14	- 95.3	12.3	0.34	0.21	50.0	33.7
12	0.63	0.19	-105.3	10.5	0.34	0.23	35.5	32.0
13	0.62	0.23	-115.6	9.6	0.32	0.24	21.7	34.0
14	0.58	0.24	-119.2	9.4	0.30	0.23	13.2	29.8
15	0.56	0.23	-123.7	10.2	0.27	0.18	2.9	37.6
16	0.53	0.20	-129.0	12.8	0.25	0.15	- 6.1	43.8
17	0.51	0.18	-134.2	12.6	0.23	0.14	- 13.1	41.5
18	0.49	0.16	138.8	15.2	0.21	0.14	- 24.3	47.8
19	0.46	0.14	-143.6	14.7	0.20	0.12	- 29.8	41.7
N	11		7		11		11	

An example, therefor, is given in Figure 10. In Figure 10a, the phase moves from 0° to -180° then jumps to +180° and decreases toward zero. In Figure 10b, which gives the results of different subjects, however, the phase moves continuously toward -180°. This discrepancy in the behaviour of phase is well known and has been described by other authors (see also Figure 2). Calculating the mean value from both types of phase curves would result in phase values of approximately zero in the higher frequency range which is obviously not correct. Since the majority of our subjects had phase curves corresponding to Figure 10b this type was chosen for the calculation of mean values.

The first maximum of all transmissibility curves in Figure 9 is located between 4 and 5 Hz. For horizontal transmissibility without backrest, a mean value of 4.5 Hz ± 0.6 results while the vertical head movements peak at 4.1 Hz ± 0.39. With backrest, the horizontal transmissibility maximum is located at 5.0 Hz ± 0.95. The vertical component has the first maximum at 4.75 Hz ± 0.45. (All values for $\bar{n}$=11).

It has been shown by our measurements that considerable horizontal motion is produced by the head under vertical (z-axis) vibration. This means that for operational conditions the published transmissibility curves for sitting humans do not represent the complete reactions of the human body to vibration stress.

To demonstrate this fact the ratio of horizontal to vertical transmissibility was calculated from the values in Table II and III and plotted versus frequency in Figure 11. From this it becomes clearly evident that without backrest 75 % of the vertical transmissibility is in the horizontal plane at resonance and remains at a level of about 50 % up to 20 Hz. By using a backrest, the horizontal fraction of transmissibility is reducted to about 35 %. It should,however, he noted that the absolute values of magnitude for vertical transmissibility are greater than those without backrest.

This behaviour of the human head under whole body vibration could also be the cause for the wide differences in vertical transmissibility often found in the literature. Our findings, therefore, confirm the assumption of Sandover [12] that differences in results may be produced by accelerometer mounting alone.

CONCLUSIONS

This first approach to measure complex head motions induced by vertical vibration should stimulate further research in this field. Especially, the head response in the frequenc range above 20 Hz is of great interest because there is evidence that the resonances of the neck and the eyes are located in this region [4a]. We were not able to conduct any experiments in the higher frequency range since the head movements become too small to be monitored with the x-y tracker. The data may be used to improve existing models for the human body and the head neck system. Further investigations of this kind

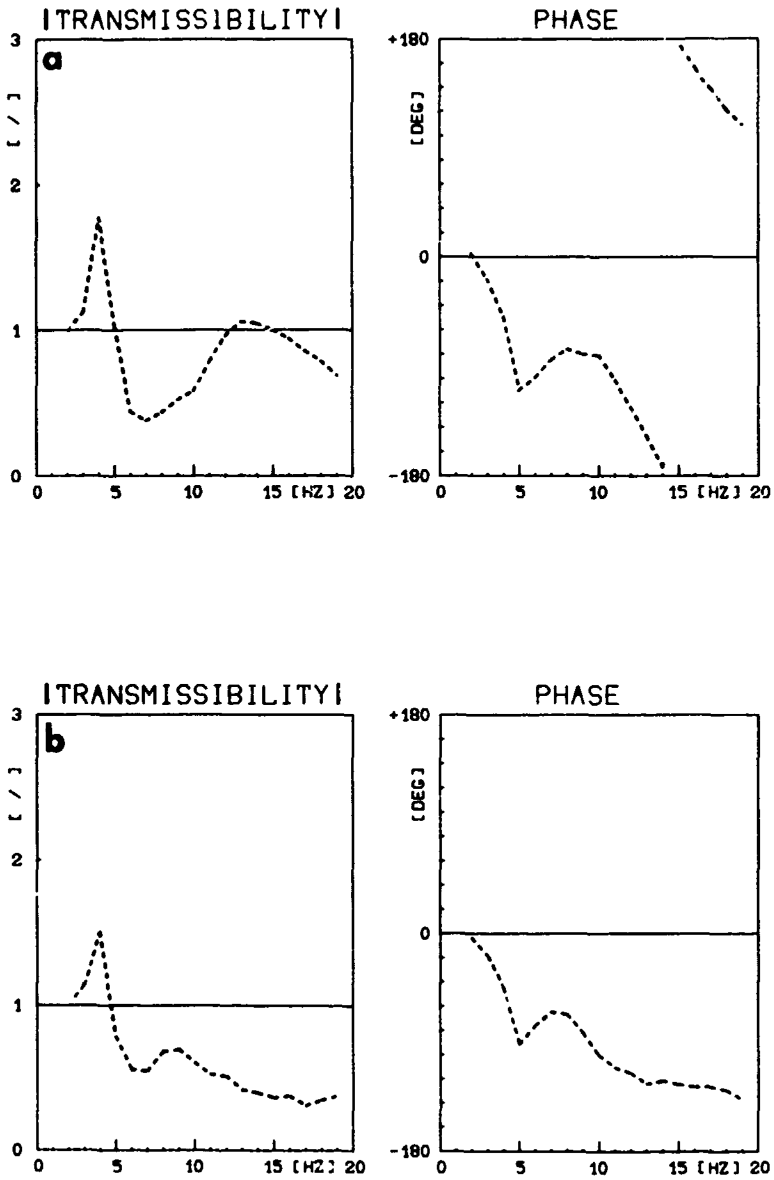

Figure 10: Vertical transmissibility and phase of two different subjects

can lead to the identification of centers of rotation for complex head and body motion. The restricted time available for our present study did not allow a thorough investigation into this field. The authors, however, have observed that the head movements in the lower frequency range investigated originate in the lower regions of the vertebral column while in the higher frequency range the cervical part of the vertebral column and the head-neck-joints present the hinges for rotary head motion. This is, however, a speculation which has to be verified in the future.

Finally, there is the question how to present standardized seat to head transmissibility values.It has already been stated, that the traditional transmissibility curve derived from head acceleration measurements,which take only the vertical component of motion into account, are not satisfactory. The way in which data are presented in this paper - that means ellipses, vertical, and horizontal transmissibility curves - are not easy to apply for practical use.

An approach to aid the understanding of human vibration response is the formulation of an adaquate mechanical model of the human body which incorporates complex head motion. Although there is still some opposition from the users side to deal with mathematical models instead of response curves, complex vibration response is more easily evaluated by a model. It will represent - if properly designed - the reactions of the body to various inputs without endangering human subjects.

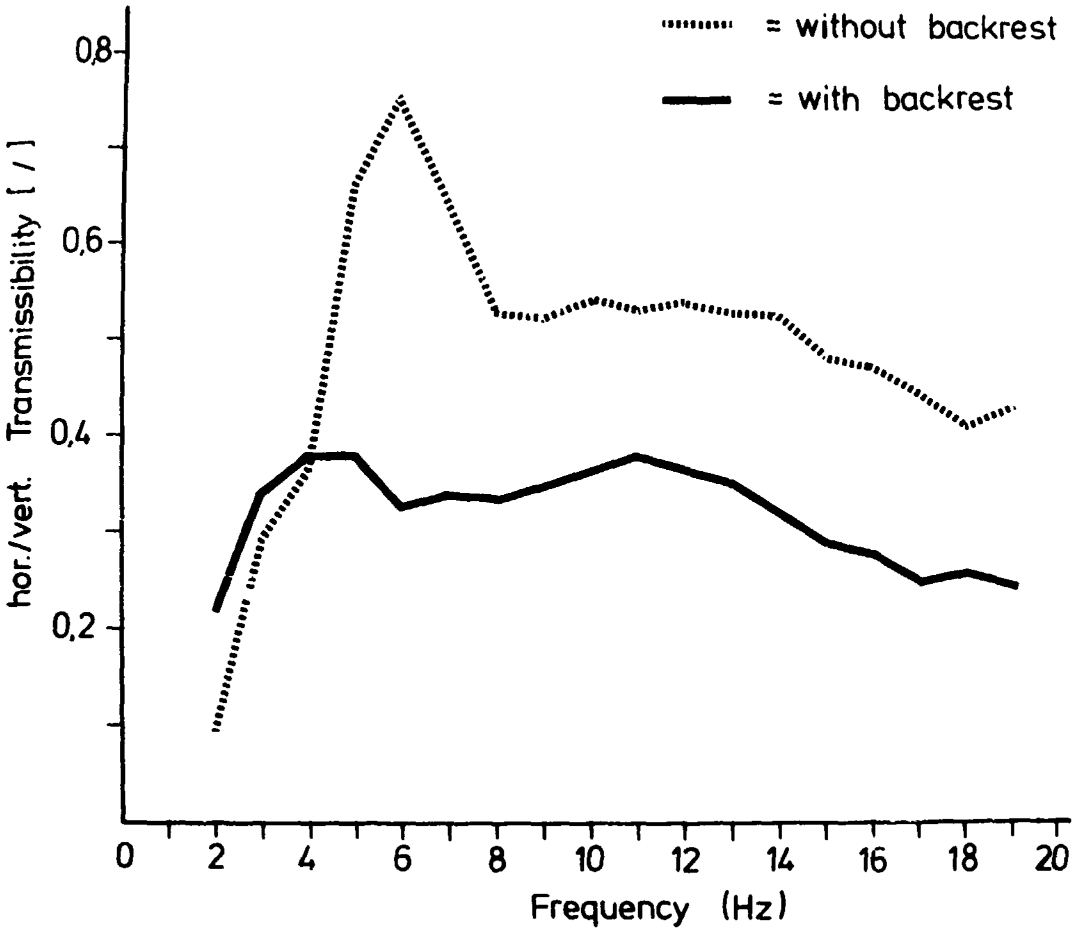

Figure 11: Ratio of horizontal to vertical transmissibility.

There is however the fact that using the modeling approach, the problems of standardizing human vibration response is only shifted to a higher level. That means, the difficulties which are created by the variability of human response is still with us.

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DISCUSSION

DR. D.J. THOMAS (US)

The loci of displacement of the head always seems to go one way - in other words, the elipse was always bent in one direction. Have you any idea why?

AUTHOR'S REPLY

No.

THE EFFECT OF RECLINED SEATING ON THE TRANSMISSION OF LINEAR VIBRATION TO THE HEAD

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SUMMARY

The transmission of vibration to the heads of subjects seated in a Martin Baker Mk 10B ejection seat exposed to vibration within the frequency range 2-25 Hz has been measured. Measurements were made for the seat conventionally mounted (back angle 20° to the vertical) and reclined for seat back angles of 30°, 45° and 60° to the vertical.

The seat was vibrated using a swept sine wave technique in either the vertical or lateral direction. Head motion in each of the three head anatomical orthogonal linear axes (g_x, g_y, g_z) was measured on a bite bar fitted with accelerometers. Ten subjects were used, each fitted with a standard Mk 2/3 flying helmet.

The results indicate that in general, for a given input, particularly in the lateral axis, head motion increased considerably when the head was in contact with the rest. Also head motion both against and off the rest increased as the seat back angle to the vertical was increased. Such increases in vibration to the head are very uncomfortable and could well lead to a performance decrement for a visual task.

1 INTRODUCTION

The increasing capability of fighter aircraft to perform sustained high acceleration turns means that human g tolerance in the conventional upright seated posture will soon be exceeded. To date, the anti-g suit has proved a valuable aid for reducing the effects of g stress on the pilot thus permitting sustained accelerations up to about 8 g_z, however for higher g levels it may be necessary to use other techniques such as reclining the pilot seat. It has long been recognised that tolerance to sustained acceleration is considerably greater when the force is applied perpendicular to the long axis of the body (g_x) rather than parallel to it (g_z). As early as 1937, Bührlen[1] showed that tolerance to g_x acceleration could be up to several seconds at 17g!

Reclined seats have been designed by Flight Systems Department (FS4), RAE[2,3] and the Institute of Aviation Medicine, Farnborough. Such seats have been used on preliminary centrifuge studies which have shown that both human blackout tolerance[4] and tracking performance[5] under g stress are higher for increased back angles of the seat. However reclined seat design means an increase (compared with an upright seat) in upper body contact pressure with the vibrating surfaces of the seat. This may increase vibration transmission to the occupant compared with an upright seat resulting in an unacceptable ride or deterioration in both manual and/or visual performance. A previous investigation[3] has measured the vibration transmission to the head of subjects seated in the FS4 reclined seat. Conclusions were that vibration levels at the head were greater when the head was against rather than off the rest.

This paper describes measurements of linear vibration at the heads of subjects seated in a standard Mk 10B ejection seat for a linear vibration input at the floor. Measurements were made with the seat mounted in the conventional upright position (with a seat back angle of 20° to the vertical) and also reclined at seat back angles of 30°, 45° and 60°. The results are in the form of vibration acceleration ratios, both single axis [vertical output acceleration/vertical input acceleration] and cross axis [lateral output acceleration/vertical input acceleration, etc] for both vertical and lateral vibration inputs.

2 CHOICE OF INPUT FUNCTION - SWEPT SINE TECHNIQUE

Seldom in real life does one encounter the sinusoidal oscillations of constant amplitude and frequency which are often used for input signals in experiments to measure body impedance or transmissibility. In such experiments subjects may be exposed to several minutes of sinusoidal oscillation whereas in real life rarely can one find records showing more than about ten oscillations. The alternative input functions are random input or swept sine input. If a random signal is used the question of statistical reliability and random error arises. It can be shown[6] that for reasonable random and bias errors and for frequencies up to about 30 Hz, record lengths of about 100-200 seconds must be considered.

For the swept sine input normally the frequency increases (or decreases) linearly with time. Past researchers who had used swept sine techniques for testing moderately damped systems had reached an empirical law which stated that for a reasonable output response signal sweep rates of approximately 1 Hz/s (for the low frequency end of the spectrum) were to be recommended. Thus swept times of 20 seconds for the 2-25 Hz bands were selected for this experiment.

However the swept sine technique although overcoming the problem of lengthy and 'unreal' experiments has disadvantages. If the response of the body to vibration inputs is non linear such that harmonics of the forcing frequency are generated then the only technique which can be used to give a general solution is of the single sine wave input type. To date there is no strong evidence to suggest that human response to vibration is non linear either in the upright or reclined postures. The second disadvantage of the swept sine technique is that by definition it is a transient and it can be shown that initial output levels can be generated which are in excess of the input amplitude. Mathematically we are still measuring cause and effect, so the calculation of the frequency response will not be affected. Investigations by Griffin *et al*[7] into the factors which may affect the transmission of vertical z axis vibration to the head over the frequency range 1-100 Hz have indicated that there was general agreement in transmissibility measures obtained using the three measurement techniques, discrete sine, swept sine, and random input.

In summary, it was felt that the single sine wave technique suffers from the requirement of a long duration experiment which imposes unnatural constraints on the subject in terms of maintaining posture etc. Since we have no evidence to suggest non linearity of the human response to vertical or lateral axis vibration it was felt that the use of a swept sine technique was preferable for this experiment.

3 EQUIPMENT

The vibration test was carried out on the RAE two-axis man-carrying vibration facility[8]. The frequency range 2-25 Hz was examined. This range was chosen since it covers most of the known human body major resonances; it also includes the main flexural frequencies of aircraft motion during turbulence. The acceleration amplitudes of 1.5 m s^{-2} and 3 m s^{-2} rms were chosen to approximate to those acceleration levels of aircraft motion experienced during moderate and extreme levels of turbulence.

3.1 Description of the seat

A Martin Baker Mk 10B ejection seat was used as shown in Fig 1. It is current in Hawk and Tornado aircraft.

A mounting frame of 6mm thick iron angle was made to support the seat both in the conventional upright position (back angle 20° to the vertical), when the head was supported vertically upright, and also reclined with back angles: 30°, 45° and 60° to the vertical (constant seat pan/back angle). A temporary foot rest was provided for the subjects in the 45° and 60° attitudes. The seat was adjusted in back length for each subject, to obtain the most comfortable position and also the correct head position on and off the rest. Seat harness was provided and was worn tightened to flight standards.

3.2 Subjects

Ten fit male subjects who were well acquainted with vibration experiments or who had previous in-flight experience were used, their height and weight being given in Table 1. Each was correctly fitted with a Mk 2/3 flying helmet without a mask.

3.3 Instrumentation

Acceleration was measured at the vibration table and also at the mouth of the seated subject. The linear accelerations of the head were measured by three Ether Type BLA2 strain gauge accelerometers mounted onto a small cube secured to the specially designed bite bar which also carried three angular accelerometers, as shown in Fig 2. The linear accelerometers were each of a half bridge strain gauge type, the other half bridge was provided in SEL carrier amplifiers Type SE 423/1. The demodulated outputs from these amplifiers were passed through low pass filters set at 30 Hz to remove the accelerometer resonance frequency before FM recording. Each linear accelerometer was calibrated by re-orientation in the earth gravitational field (±1g) and the dc outputs were measured. The total weight of the bite bar, dental mould and accelerometers was approximately 300 grams. The main contribution to the weight was from the angular accelerometers, the results from which are to be included in a separate report, however these were the smallest commercially available at the time. This additional weight on the head due to the bite bar and accelerometers was comparable with that of an oxygen mask and hose which is normally worn during flight. However for these trials no oxygen mask could be worn because of the use of the bite bar - and the assumption was therefore made that the bite bar and mask provided an equivalent dynamic loading.

3.4 Analysis

The recorded signals were passed through low pass anti-aliasing filters set at 25 Hz prior to analysis via fast Fourier transform [FFT] techniques on a Hewlett Packard Fourier analyser Type 5451B. Acceleration ratios were computed by dividing the output spectrum of the head vibrations for each of the three orthogonal linear axes by the linear spectrum of the approximate simultaneous (input) table vibration. Results for all the subjects were compared for each condition. The typical acceleration ratio response from one subject out of the ten has been shown for each vibration/seating condition in Figs 3 to 10.

The vibration measurements presented in this paper are with reference to the three anatomical linear axes of the head (defined in Ref 9) since it is to these reference axes that most human factors data are referred.

4 EXPERIMENTAL PROCEDURE

The seat was adjusted for each subject and the seat harness tightened to flight standards. The subject sat relaxed with his feet on the floor (or resting on the foot rest for inclinations of 45° and 60°) and hands resting on thighs. Subjects were instructed to maintain an alert posture during each 20 second vibration exposure with eyes fixed on a point on the vibrator room wall. Subjects were observed to make sure that the postures used were representative and consistent. The variation in body posture possible within the tight strapping conditions over the 20 second duration of the frequency sweep was found to be small.

Acceleration ratio measurements were made using a frequency sweep 2-25 Hz, lasting 20 seconds with a nominally constant input acceleration amplitude. Table 2 gives the vibration conditions used for each test. Two acceleration levels 1.5 $m\,s^{-2}$ and 3 $m\,s^{-2}$ rms as measured at the vibration table were used in each of the vertical and lateral axes. The cross axis response of the vibration rig was less than 5%, *ie* vertical input produced negligible lateral motion and vice versa. The subject was exposed to each vibration condition twice, once with his head held firmly against, and once with his head just off the rest.

5 RESULTS

Figs 3 to 6 show typical vibration table to subject head acceleration ratios for a vertical input vibration and Figs 7 to 10 those for a lateral input vibration for each seating condition: 20° (conventional), 30°, 45° and 60° seat back angles to the vertical. The ranges of frequency and acceleration ratio of the main peaks (numbered 1 and 2 in Figs 3 to 10) in the response of each of the ten subjects are shown in Table 3. Initial investigations of the vibration response of the seat head rest *per se* did not indicate any vertical or lateral resonances.

5.1 Vertical vibration input

5.1.2 The effect of reclined seating on vertical axis head motion

Figs 3(i) to 6(i) show the acceleration ratios of vertical vibration to the head when the seat was mounted with seat back angles to the vertical of: 20° (conventional), 30°, 45° and 60° respectively.

When the head was against the rest there were two peaks in the vertical acceleration ratio indicated at 4-6 Hz and 8-14 Hz for all seating conditions for both levels of input vibration. The frequencies of these peaks correspond to main shoulder and head resonances[10]. The amplitude ratios of the 4-6 Hz peak remained within the same ranges of 0.7-1.8 and 0.6-2.2 for the 3 $m\,s^{-2}$ and 1.5 $m\,s^{-2}$ input conditions respectively for all seating conditions. The amplitude of the 8-14 Hz peak increased as the seat was reclined to 60° to 2.4-3.2 at 3 $m\,s^{-2}$ input and to 1.5-3.7 at 1.5 $m\,s^{-2}$ input.

When the head was off the rest there were also two peaks in vertical acceleration ratio at 5-8 Hz and 9-14 Hz for all seating conditions except the 30° seat for the 1.5 $m\,s^{-2}$ vibration input level. In this condition the 5-8 Hz peak was not evident, but may have been masked in the larger amplitudes of the 9-14 Hz peak (amplitude 2.3-3.8). For the conventionally mounted (20° back angle) case, the amplitudes of the peaks when the head was off the rest were similar to those with the head against the rest for both input conditions. However, as the seat was reclined the amplitudes of both peaks increased. The amplitudes of the 5-8 Hz peaks increased from 1-1.6 and 1-2.2 for the 3 $m\,s^{-2}$ and 1.5 $m\,s^{-2}$ input conditions respectively for a conventionally mounted seat to 1.8-2.8 and 1.5-3 for a seat mounted with a 60° back angle.

It is interesting to note that when the head was held against the rest the amplitude of the main resonance at 4-6 Hz remained constant as the seat was reclined which resulted in the head on shoulder resonance or possible pitching resonance[11] of the head at 8-14 Hz predominating at a 60° seat back mounting. Whereas when the head was off the rest both resonances were of nominally equal magnitudes for all seat back angles with the curious exception of the 30° seat inclination.

5.1.2 The effect of reclined seating on cross-axis lateral head motion

Figs 3(ii) to 6(ii) show the acceleration ratios of cross axis lateral vibration (lateral output/vertical input) to the head when the seat was mounted at various back angles to the vertical.

When the head was against the rest there was a single peak in response at between 7 and 13 Hz for all seat conditions and input conditions. This corresponds to a possible resonance of the head at about 8 Hz as indicated in the work by Barnes and Rance[12]. This work showed an increase in roll motion at about 8 Hz when a subject was vibrated in yaw. When the head was against the rest the point of contact head to rest acted as a pivot point of motion. Any roll motion of the head about this pivot point would produce a lateral component when measured at the mouth (about 0.2 m in front of the pivot point). This peak at 7-13 Hz was most apparent for the low 1.5 $m\,s^{-2}$ input condition when it increased from an amplitude of 0.6-4 for the upright seat to 3.4-6 for the 60° mounted seat. When the head was removed from the rest the acceleration ratios were greatly reduced to below 0.5 for most conditions.

5.1.3 The effect of reclined seating on cross-axis fore/aft head motion

Figs 3(iii) to 6(iii) show the effect of reclined seating on the acceleration ratios of cross axis fore/aft vibration to the head.

When the seat was mounted conventionally and also when reclined to a back angle of 30° to the vertical the acceleration ratio was low, peaks occurring of amplitudes up to 1 for frequencies below 10 Hz and was less than 0.3 for frequencies above 10 Hz when the head was against or off the rest. For the seat reclined at 45° there were two peaks in response when the head was against the rest. The peaks occurred at 7-9 Hz and 11-15 Hz. These were within the amplitude range of 0.5-1.4 and 0.3-1.1 for each input condition respectively. When the head was lifted off the rest the 11-15 Hz peak disappeared and the 7-9 Hz peak was reduced in amplitude to below 0.7. When the seat was further reclined to 60° the acceleration ratios for all vibration conditions showed a peak at 6-9 Hz When the head was against the rest this peak had an amplitude of 1-2 and 1-2.5 respectively for the 3 m s^{-2} and 1.5 m s^{-2} input conditions. When the head was lifted off the rest the amplitudes of the peaks were approximately halved.

5.2 Lateral vibration input

5.2.1 The effect of reclined seating on cross-axis vertical head motion

Figs 9(i) and 10(i) show the acceleration ratios of cross axis vertical vibration to the head when the seat was reclined at 45° and 60° back angles. For other seat mounting angles the cross axis response of vertical vibration to the head was small (< 0.8) for both head against or off the rest. At back angles of 45° and 60° when the head was on the rest peaks in response of up to 1 were found at 5-10 and 12-14 Hz for the 3 m s^{-2} input condition. For the 1.5 m s^{-2} input condition of the 45° seat only one peak was indicated at 11-15 Hz of amplitude 0.7-1.6 but for the 60° back angle two peaks again occurred at 6-9 Hz and 13-15 Hz These peaks correspond well with head and head on shoulder resonances.

When the head was lifted off the rest for the 45° back angle one peak was indicated at 5-12 Hz (amplitude 0.5-0.6) for the 3 m s^{-2} input and at 12-13 Hz (amplitude 0.3-1.1) for the 1.5 m s^{-2} input. For the 60° back angle a single peak was indicated at 5-9 Hz (amplitude 0.3-0.9 for 3 m s^{-2} input and 0.5-1.4 for 1.5 m s^{-2} input conditions).

5.2.2 The effect of reclined seating on lateral axis head motion

Figs 7(ii) to 10(ii) show the acceleration ratio responses of lateral vibration to the head for the various seat back angles.

When the head was against the rest for all vibration conditions and seat back angles there was a peak in response at 5-12 Hz. Its amplitude for the 3 m s^{-2} input of 2.1-4.1 for the conventional 20° seat mounting position was reduced to 0.5-2.5 and 1.5-2.7 for the 30° and 45° reclining positions respectively but was rather higher (2.5-3.2) for the 60° back angle. For the 1.5 m s^{-2} input the amplitudes were slightly higher than for the 3 m s^{-2} input but showed the same trend with seat back angle. For the 20° and 45° back angles for both input conditions there was also a peak at 15-18 Hz of amplitude for the 3 m s^{-2} input condition of 0.9-2.5 and 0.4-1.2 respectively for each seat condition and for the 1.5 m s^{-2} input of 0.7-3 and 0.6-2.2 respectively. These 15-18 Hz peaks were probably masked in intersubject scatter for the other back angles.

When the head was lifted off the rest the acceleration ratio was greatly reduced (< 0.3) for frequencies above 4 Hz for all vibration and seat conditions. Below 4 Hz there was some indication of peaks in response but with maximum amplitudes of 1.

5.2.3 The effect of reclined seating on cross axis fore/aft head motion

Figs 9(iii) and 10(iii) show the acceleration ratios of cross axis fore/aft vibration to the head when the seat was mounted at 45° and 60° seat back angles. For other seat mounting angles the acceleration ratios showed large intersubject scatter and were less than 0.5 for both head against or off the rest.

At seat back angles of 45° and 60° when the head was against the rest for both input conditions there were two peaks in transmission at 6-10 and 12-15 Hz of amplitudes 0.1-0.7 and 0.2-0.6 respectively for both input conditions at a 45° back angle and amplitudes 0.3-1.1 and 0.8-1.7 respectively for both input conditions at a 60° back angle.

When the head was lifted off the rest the amplitudes of any peaks was minimal (less than 0.6) and intersubject scatter was increased.

6 CONCLUSIONS AND FURTHER WORK

Transmission of vibration to the head increased as the seat back angle to the vertical was increased. This was most evident when the head was against the rest, particularly in the lateral axis for a vertical input vibration at the 1.5 m s^{-2} input level. For some conditions there was a large reduction in transmission for increased acceleration level input. This was possibly due to two main factors. Firstly stiffening up of the neck muscles under the more uncomfortable higher vibration input conditions. Secondly for some conditions there was a large intersubject variability. This may have been due not only

to the different biomechanical characteristics of each subject but also the various extents to which each subject pressed his head against the rest. When the vibration was more uncomfortable he pressed his head less hard. The amplitude results presented in this paper must be interpreted with care, however, they do indicate the approximate frequencies of maximum head motion. If a reclined seat design is to be practical the pilot's head has to be supported for all or most of the time by a head rest. These results show a large increase in vibration transmitted to the head, when it is held against a rest. This increase in vibration would probably be unacceptable from a consideration of comfort and performance of visual tasks. Since the transmission of vibration to the head when the head was off the rest did not increase so dramatically with increasing seat angle, it would seem that with an efficient vibration isolating head rest the use of an inclined pilot's seat would not adversely affect a pilot's vibration rating of a 'ride' in terms of comfort and task performance, as compared to a seat without such an isolator.

Table 1

Subject parameters

Subject No.	Age (years)	Height (m)	Weight (kg)
1	36	1.73	60.3
2	25	1.78	73
3	29	1.79	69
4	40	1.79	70.6
5	38	1.75	62.2
6	42	1.67	60
7	35	1.79	61.2
8	32	1.80	63.5
9	30	1.79	66.6
10	33	1.80	76.2

Table 2

Test conditions

Frequency range 2-25 Hz				
Test No.	Acceleration level (m/s^2)		Subject posture	
	3.0	1.5	Head on	Head off
1	/		/	/
2	/	/	/	/
3		/	/	
4		/		/

Table 3

The ranges in frequency and acceleration ratio of the major peaks (10 subjects)

Vertical input:

Output axis	Vertical								Lateral					Fore/aft			
Head position on rest	On				Off				On			Off		On		Off	
Input acceleration level m s^{-2}	3		1.5		3		1.5		3	1.5		3	1.5	3	1.5	3	1.5
Seat angle 20°																	
Peak number	1	2	1	2	1	2	1	2	1	1	2			1	1	1	1
Acceleration ratio range:																	
Upper	1.6	1.8	2.2	2.4	1.6	1.5	2.2	1.7	1.2	4	1.2	<0.4	<0.7	1	1	1.3	1.3
Lower	0.9	0.7	0.6	1	1	1	1	0.8	0.3	0.6	0.2			0.3	0.2	0.2	0.1
Frequency range, Hz																	
Upper	6	12	7	13	6.5	11	6.5	13	11	10	18	Large	Large	7.5	8.5	6	6.5
Lower	4.5	8	5	10	5	10	5.5	11.5	7.5	8	17	Scatter	Scatter	5	6	3	3
Seat angle 30°																	
Peak number	1	2	1	2	1	2	2		1	1				1		1	1
Acceleration ratio range:																	
Upper	1.7	2.2	2.2	3.[illegible]	2.3	3.2	3.8		1.2	2.1		<0.3	<0.9	<1.0	<0.7	1.1	1.1
Lower	1.2	0.5	0.8	1.3	1.5	1.5	2.3		0.5	0.2						0.1	0.3
Frequency range, Hz																	
Upper	5	12	6.5	14	7	11	13		9	13		Large	Large	Large	Large	7	10
Lower	4	8	5.5	10	[illegible]	9	9		5	9		Scatter	Scatter	Scatter	Scatter	5	8

Table 3 (continued)

Vertical input (concluded):

Output axis	Vertical								Lateral				Fore/aft					
Head position on rest	On				Off				On		Off		On				Off	
Input acceleration level, m s^{-2}	3		1.5		3		1.5		3	1.5	3	1.5	3		1.5		3	1.5
Seat angle 45^{o}																		
Peak number	1	2	1	2	1	2	1	2	1	1			1	2	1	2	1	1
Acceleration ratio range:																		
Upper	1.8	2.3	1.9	4	2	2	2.6	2.1	1.2	4.2	<0.5	<0.5	1.2	1.1	1.4	1	0.7	0.7
Lower	0.7	1.6	1	2.6	0.9	1.2	1.2	1.4	0.6	1.6			0.5	0.4	0.7	0.3	0.1	0.1
Frequency range, Hz																		
Upper	6	12	6	11	7	11	8	14	10	9	Large	Large	8	14	9	15	8	9
Lower	5	8	4.5	8	5	9	4.5	9	7	8	Scatter	Scatter	7	11	7	11	7	7
Seat angle 60^{o}																		
Peak number	1	2	1	2	1	2	1	2	1	1			1		1		1	1
Acceleration ratio range:																		
Upper	1.6	3.2	1.9	3.7	2.4	2	3	2.5	1.5	6.6	<0.4	<0.5	2		2.5		1.2	1
Lower	1.2	2.4	1	1.5	1.8	1.1	1.5	1.5	0.6	3.4			1		1		0.5	0.8
Frequency range, Hz																		
Upper	5	13	6	14	8	12	8	14	11	10	Large	Large	8		9		8	9
Lower	4.5	12	5	8	5	9	5	11	8	7	Scatter	Scatter	6		7		7	7

Lateral input:

Output axis	Vertical				Lateral						Fore/aft			
Head position on rest	On		Off		On				Off		On		Off	
Input acceleration level, m s^{-2}	3	1.5	3	1.5	3		1.5		3	1.5	3	1.5	3	1.5
Seat angle 20^{o}														
Peak number					1	2	1	2	1	1				
Acceleration ratio range:														
Upper	<0.7	<0.8	<0.3	<0.5	4.1	2.5	4.7	3	0.6	0.6	<0.5	<0.5	<0.2	<0.2
Lower					2.1	0.9	1.9	0.7	0.2	0.2				
Frequency range, Hz														
Upper	Large	Large	Large	Large	9	17	11	18	4	4	Large	Large	Large	Large
Lower	Scatter	Scatter	Scatter	Scatter	8	16	9	16	3	3	Scatter	Scatter	Scatter	Scatter
Seat angle 30^{o}														
Peak number					1		1							
Acceleration ratio range:														
Upper	<0.4	<0.5	<0.5	<0.4	2.5		1.6		<1	<1	<0.5	<0.4	<0.3	<0.2
Lower					0.5		0.3							
Frequency range, Hz														
Upper	Scatter	Scatter	Scatter	Scatter	9		10		Scatter	Scatter	Scatter	Scatter	Scatter	Scatter
Lower					5		5							

Table 3 (concluded)

Lateral input (concluded):

Output axis	Vertical						Lateral						Fore/aft						
Head position on rest	On				Off		On				Off		On				Off		
Input acceleration level, m s⁻²	3		1.5		3	1.5	3		1.5		3	1.5	3		1.5		3	1.5	
Seat angle 45°																			
Peak number	1	2	1			1	1	2	1	2	1	1	1	2	1	2			
Acceleration ratio range:																			
Upper	1	1	1.6		0.6	1.1	2.7	1.2	3.3	2.2	0.6	1	0.7	0.4	0.5	0.6	<0.3	<0.3	
Lower			0.7		0.5	0.3	1.5	0.4	1.8	0.6	0.3	0.3	0.1	0.2	0.2	0.3			
Frequency range, hz																			
Upper	10	14	15		12	13	12	16	14	17	3	4	9	15	9	13	Large	Large	
Lower	8	13	11		5	12	6	14	6	15	2	1.5	6	14	8	14	Scatter	Scatter	
Seat angle 60°																			
Peak number	1	2	1	2	1	1	1		1		1	1	1	2	1	2	1	1	2
Acceleration ratio range:																			
Upper	1	1	1	1.2	0.9	1.4	3.2		4.1		1	1	1.1	1.4	1	1.7	0.6	0.6	0.6
Lower	0.3	0.2	0.4	0.4	0.3	0.5	2.5		3.0		0.4	0.4	0.4	0.8	0.3	1	0.1	0.3	0.1
Frequency range:																			
Upper	8	14	9	15	9	9	8		10		3	5	9.5	14	9	15	9	10	13
Lower	5.5	12	6	13	5	6	6		7		1	4	3	12	8	13	8	9	12

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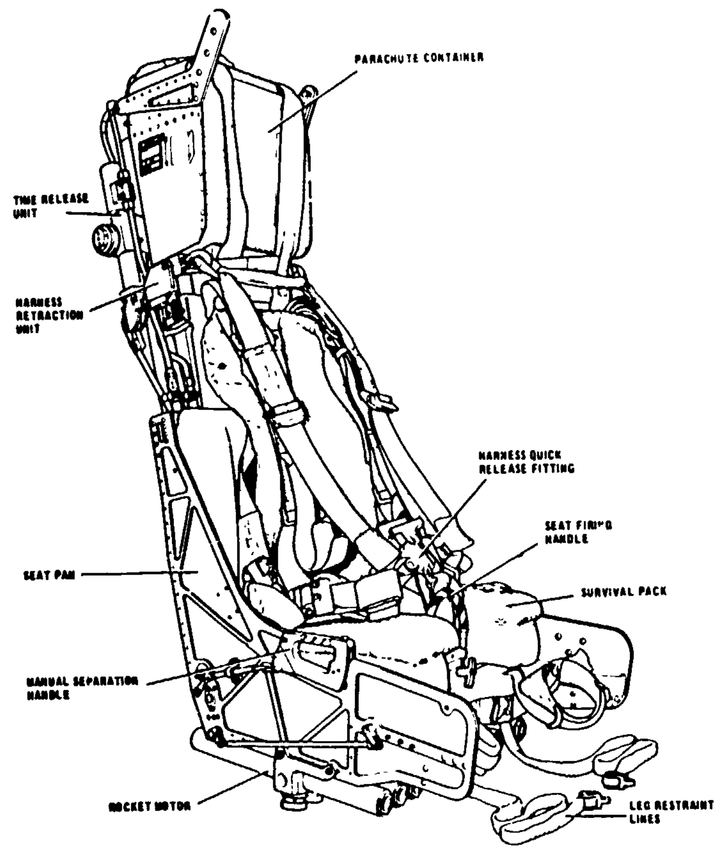

Fig 1   Mk 10B ejection seat

Fig 2 [illegible]

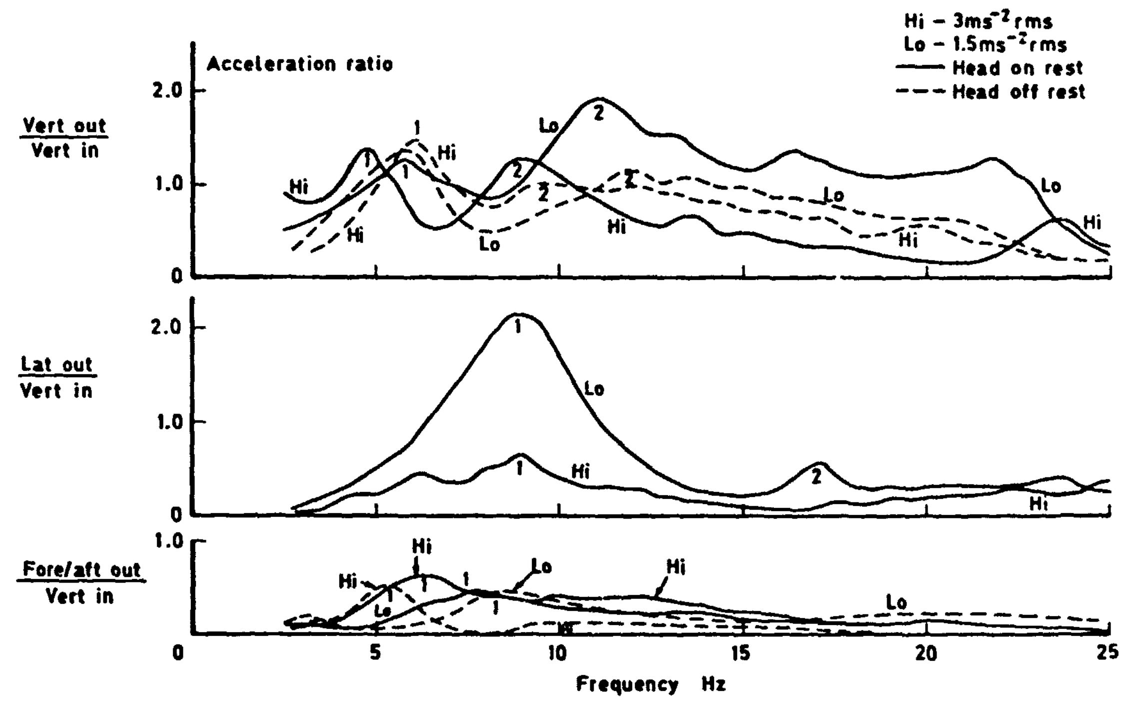

Fig 3 Mk 10B ejection seat - seat back angle 20° to the vertical. Typical acceleration ratios for a constant amplitude swept sine input. Vertical vibration input

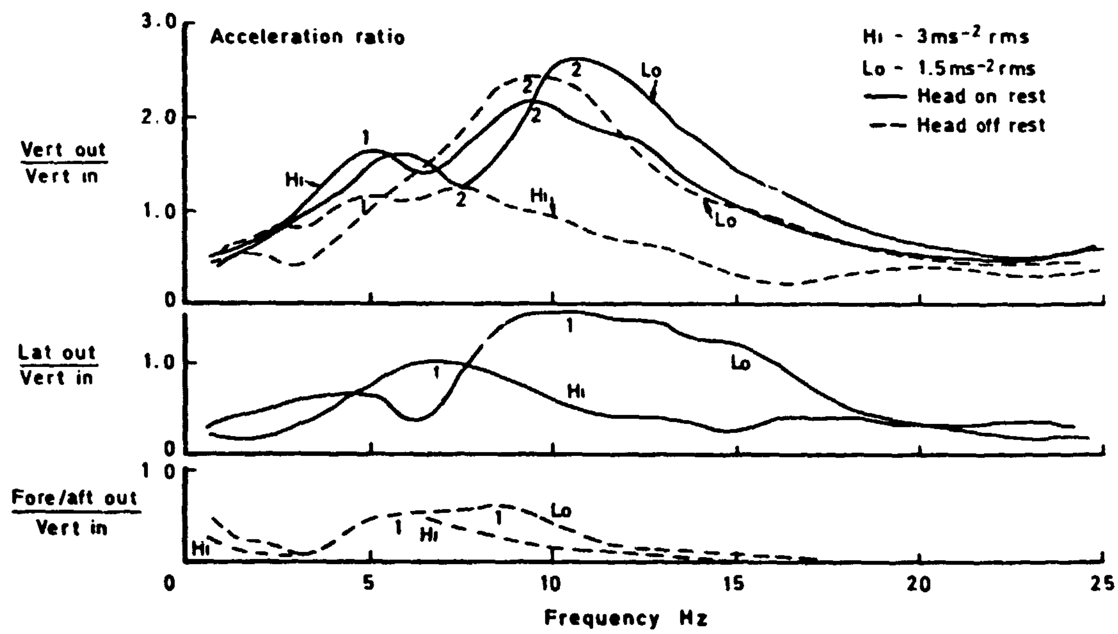

Fig 4 Mk 10B ejection seat - seat back angle 30° to the vertical. Typical acceleration ratios for a constant amplitude swept sine input. Vertical vibration input

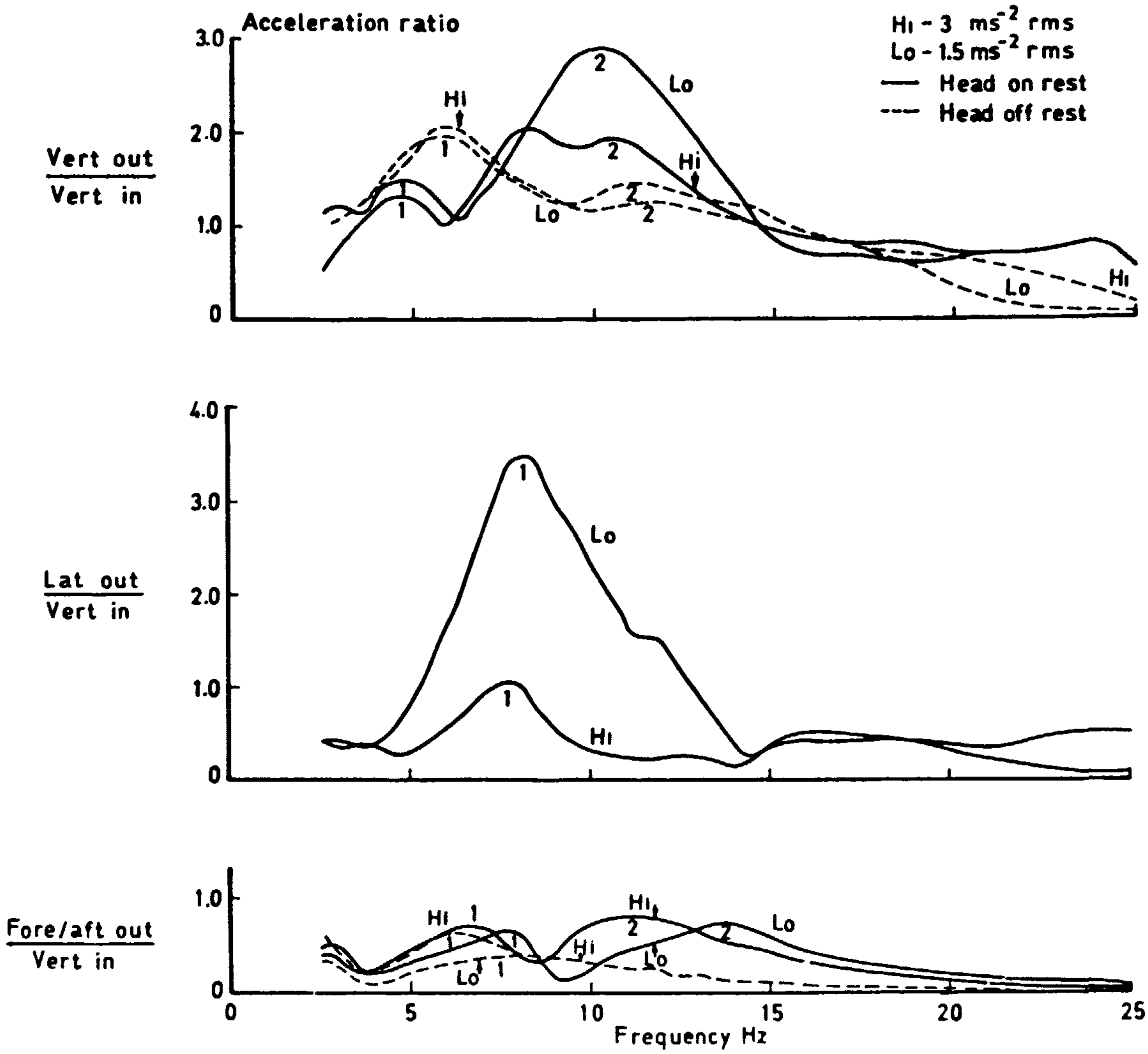

Fig 5 Mk 10B ejection seat - seat back angle 45^0 to the vertical. Typical acceleration ratios for a constant amplitude swept sine input. Vertical vibration input

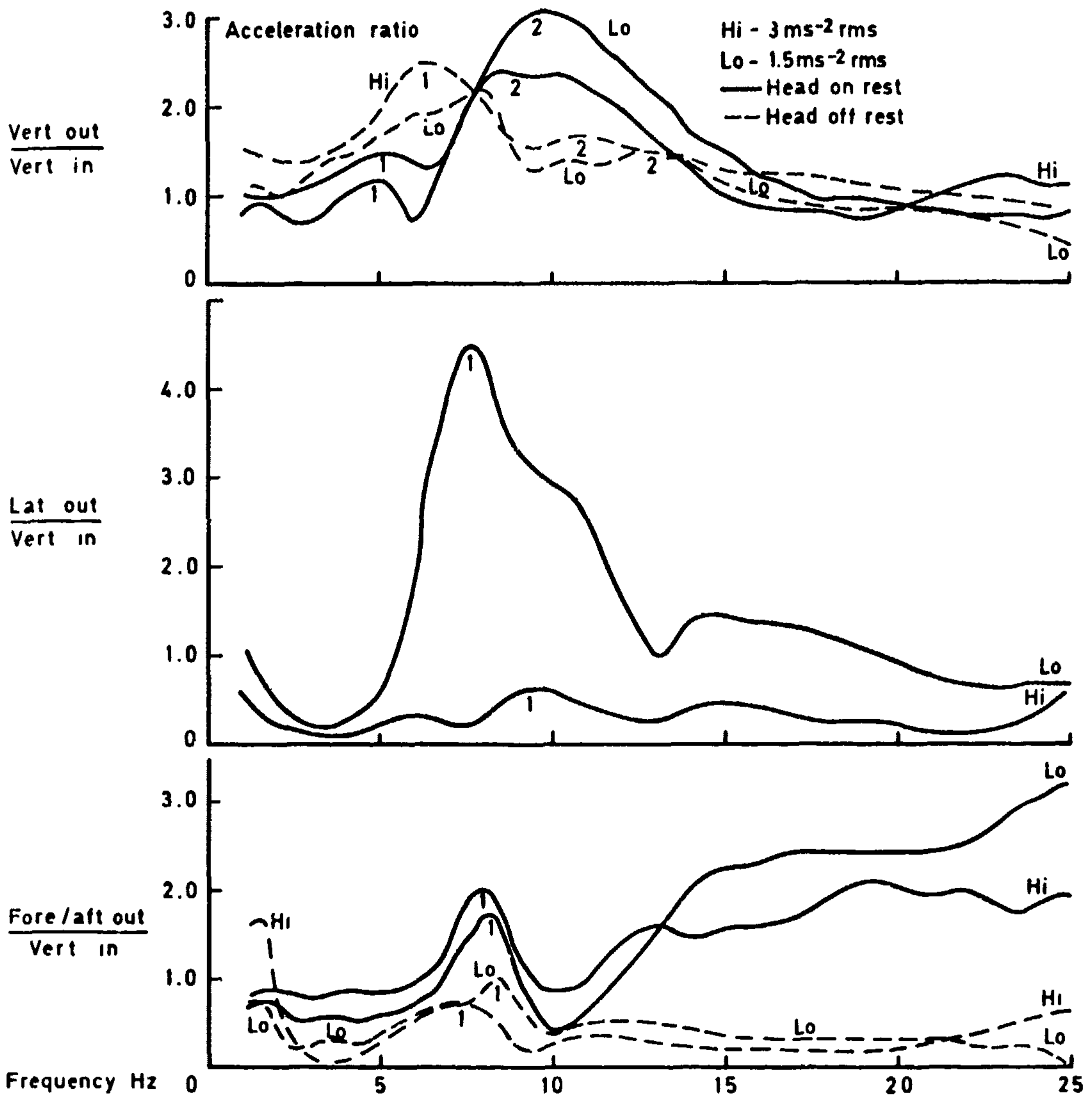

Fig 6 Mk 10B ejection seat - seat back angle 60° to the vertical. Typical acceleration ratios for a constant amplitude swept sine input. Vertical vibration input

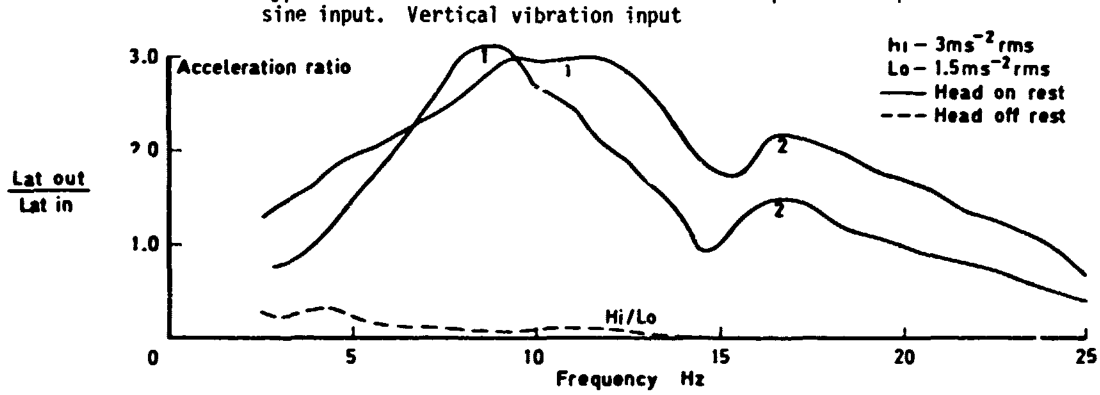

Fig 7 Mk 10B ejection seat - seat back angle 20° to the vertical. Typical acceleration ratios for a constant amplitude swept sine input. Lateral vibration input

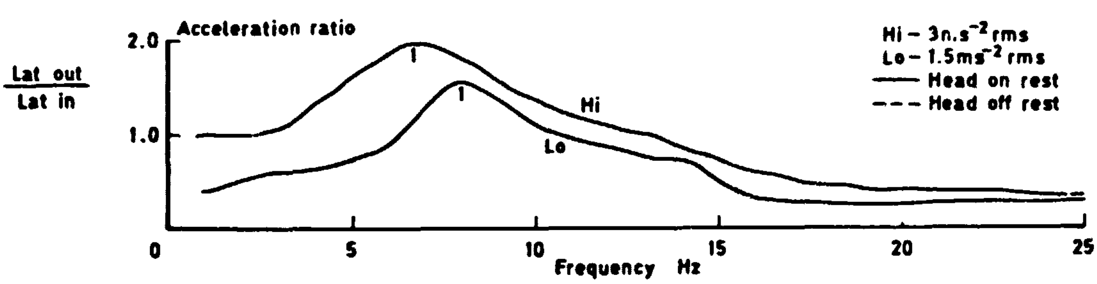

Fig 8 Mk 10B ejection seat - seat back angle 30° to the vertical. Typical acceleration ratios for a constant amplitude swept sine input. Lateral vibration input

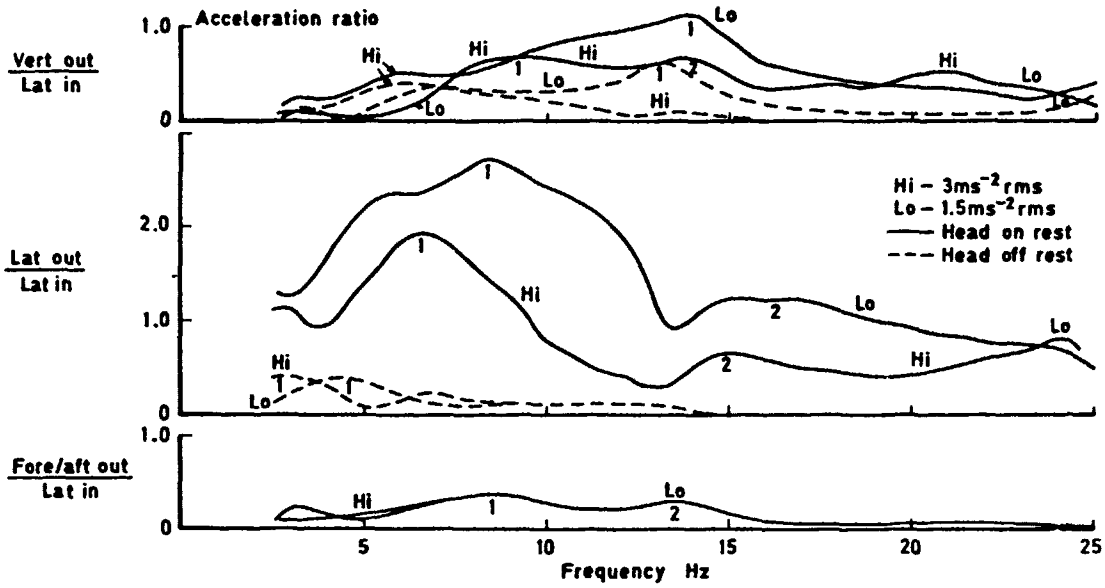

Fig 9 Mk 10B ejection seat - seat back angle 45^{0} to the vertical. Typical acceleration ratios for a constant amplitude swept sine input. Lateral vibration input

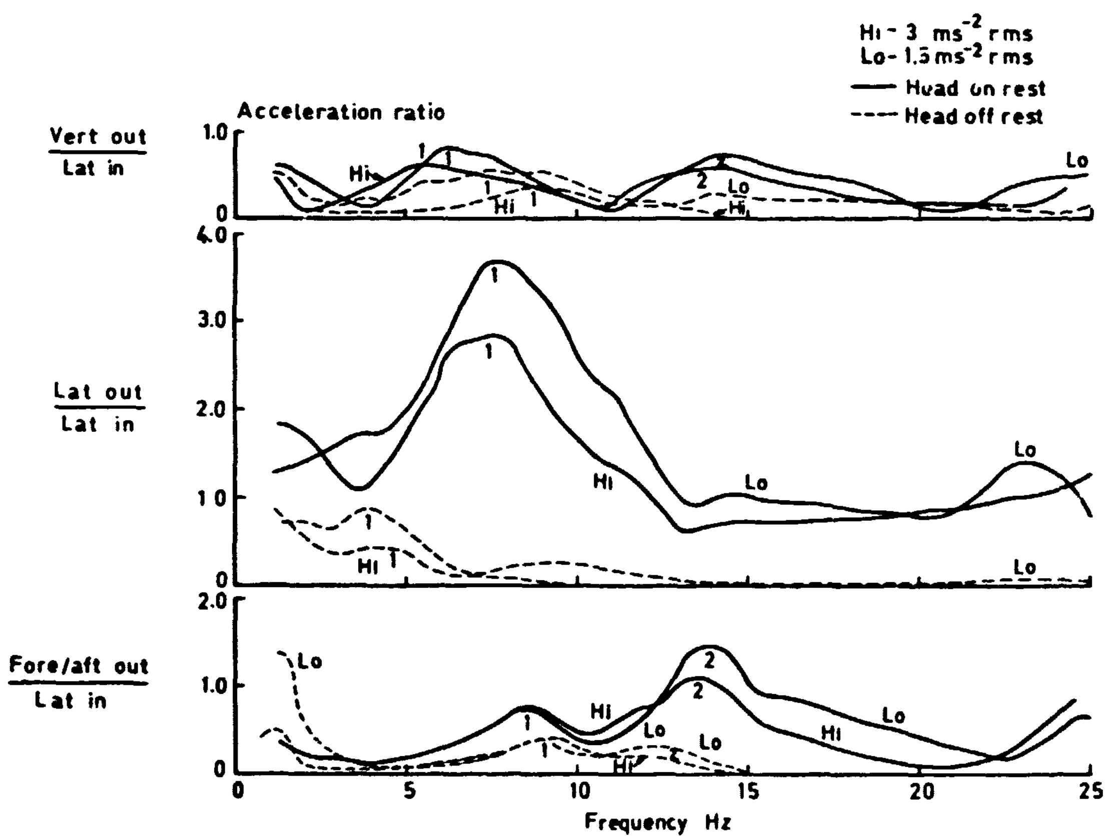

Fig 10 Mk 10B ejection seat - seat back angle 60^{0} to the vertical. Typical acceleration ratios for a constant amplitude swept sine input. Lateral vibration input

DISCUSSION

LT.COL. W. VONRESTORFF (FRG)

Did you ensure, during inclination of the seat, that the head co-ordinates remained constant with respect to earth co-ordinates?

AUTHOR'S REPLY

The vibration measurements reported are with respect to the anatomical co-ordinates of the head, since it is in these co-ordinates that previous human-factors data were recorded. As the seat was reclined, these head co-ordinates diverged from the earth co-ordinates. However, we were interested in the effect of reclining the Mk 10B ejection seat on the transmission of vibration to the head. To have maintained the head in a vertical position would have required an additional, non standard, headrest, and would have contributed an additional variable.

LT. COL. W. VONRESTORFF (FRG)

Why did you use identical acceleration inputs in both vertical and lateral axes?

AUTHOR'S REPLY

This was done for consistency. These conditions include the main flexural frequencies of aircraft motion during turbulence and embrace the known human body resonances.

WG.CDR. D.H. GLAISTER (UK)

How representative was the headrest used in the reclined seat? In view of its deleterious effect on vibration transmission, have you looked into a headrest incorporating some form of vibration isolation?

AUTHOR'S REPLY

The standard Martin Baker Mk 10B ejection seat headbox was used. We have done tests on reclined seats fitted with solid headrests and in general head motion increased considerably with head contact. The design of a headbox to incorporate vibration isolation is included as a possible item on our future programme of work.

GEN. J. FORESTIER (FR)

The exact definition of the seat is still unclear to me. Was it a standard Mk 10B with fixed headrest as referred to in the text, or a similar seat with some kind of headrest "supporting the head vertically upright for all back angles of the seat" as shown in your figure 2?

AUTHOR'S REPLY

I am sorry for the confusion. Figure 2 was intended only to illustrate the acceleration measuring technique using a bite-bar. The seat was a standard Mk 10B fitted with its standard headbox. No additional head support was used so the head was not held vertically upright for all seat back angles.

THE EFFECTS OF AIRCRAFT VIBRATION ON VISION

by

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SUMMARY

Movements of the head resulting from aircraft vibration can result in a decrement in visual performance as a result of limitations in the response of two mechanisms, the pursuit reflex and the vestibulo-ocular reflex, which are responsible for eye stabilization. A series of experiments has been conducted in order to assess: (a) the frequency characteristics of the vestibulo-ocular and pursuit reflexes; (b) the ability of subjects to suppress reflex vestibular eye movements which become inappropriate when viewing a helmet-mounted display; (c) the effect of relative movement between the eye and the viewed object on visual performance, and (d) the biodynamic response of the head during vibration which gives rise to stimulation of the vestibular system. The results of these experiments are discussed in an attempt to estimate the effects of aircraft vibration on visual performance.

INTRODUCTION

The ability of aircrew to maintain visual acuity is essential for the proper control of the aircraft. Vibration at the head can, under specific conditions, cause movement of the retinal image and hence impair visual acuity as a result of image smear. One such condition arises during stimulation of the vestibular apparatus of the inner ear, which induces reflex eye movements, the function of which is to compensate for head movement and thus stabilize the eye in space. As a consequence man is able to maintain fixation of earth-fixed objects during vibration and to preserve visual performance at levels comparable to those for static conditions. However, if the object of fixation is also subject to the same vibration, the vestibularly induced eye movement is inappropriate and must be suppressed or modified for visual acuity to be preserved. This effect is particularly relevant to the use of helmet-mounted display systems, in which the head and display move simultaneously.

A number of experiments, which are summarized here, have been conducted in an attempt to estimate the ability of human subjects to suppress inappropriate eye movements under specific vibration conditions and to interpret the smeared retinal image characteristics which result from incomplete suppression. The severity of the problem is assessed in the light of information about the biodynamic response of the head to aircraft vibration.

EYE MOVEMENT CONTROL MECHANISMS

In man, there are two neural control mechanisms which serve to stabilize the image of a seen object upon the foveal retina (1). One, the vestibulo-ocular reflex, is an open-loop system which makes use of information from the vestibular apparatus to generate eye movements compensatory to the angular motion of the head. The other, the pursuit or fixation reflex, is a closed-loop system which uses information from the retina to produce eye movements that track the moving object in order to maintain a foveal image. Thus, the ability to predict whether visual acuity will be impaired in a particular motion environment depends upon an understanding of: (a) the dynamics of each of these oculomotor control systems; (b) the mechanisms which give rise to the blurred images associated with movement of the image across the retina; and (c) a quantitative description of the motion of the observers head and the relative motion between the visual target or display and his head.

The principal response of the vestibulo-ocular reflex is that which arises from angular motion of the head. On either side of the head three semicircular canals, disposed in orthogonal axes, sense movement of the head and effectively transduce head angular velocity over a wide range of frequencies (0.05-5 Hz). Experiments (1) in which eye movements have been recorded during angular acceleration of the head have shown that this reflex mechanism is highly effective at eye stabilization within the frequency range of natural head movement (0.5-2Hz) where the relationship between eye velocity and head velocity exhibits a gain close to unity and a phase difference of 180°. There is a second type of response which originates from stimulation of the otoliths, receptors within the vestibular system which are sensitive to linear acceleration. Recent experiments (2) have shown that eye velocities of 3-4°/s per m/s^2 may be expected in response to both vertical and lateral linear oscillation. However, the functional significance of such rotational eye movements in response to phasic linear acceleration is unclear at present.

The need for a system to stabilize the retinal image becomes apparent when one considers the limitations of the visually induced reflex mechanisms by which man is able to maintain fixation on a moving object. It has been well established (3,4,5,6,11) that the visually driven pursuit reflex breaks down either when the velocity of target movement is too great (>40-60°/s) or when the frequency of a direction changing movement is too high (>1-2 Hz). The rapid decline in gain of the pursuit reflex and the development of large phase lag at frequencies above 1 Hz has been well established by recording eye movements during attempts to follow oscillating targets (4). Associated with this breakdown is an inability to preserve visual acuity. This feature is demonstrated by the results shown in fig. 1, which summarises the results of an experiment (1,7) in which subjects were required to read, as quickly and as accurately as possible, a display consisting of an 8 x 8 digit matrix. Each digit subtended 8 min arc and had a luminance of 7.0 cd/m^2 against a background of 0.7 cd/m^2. Measures of reading performance, expressed as the number of digits read in a 10 sec period and the percentage of errors made, were obtained during sinusoidal oscillation of the display in yaw at frequencies in the range 0.5-10 Hz; peak velocity was maintained at ±30°/s. Control measures were taken with the display stationary at the beginning and end of a test session. The measures of visual performance (fig. 1) reveal that even at 0.5 Hz there was a significant

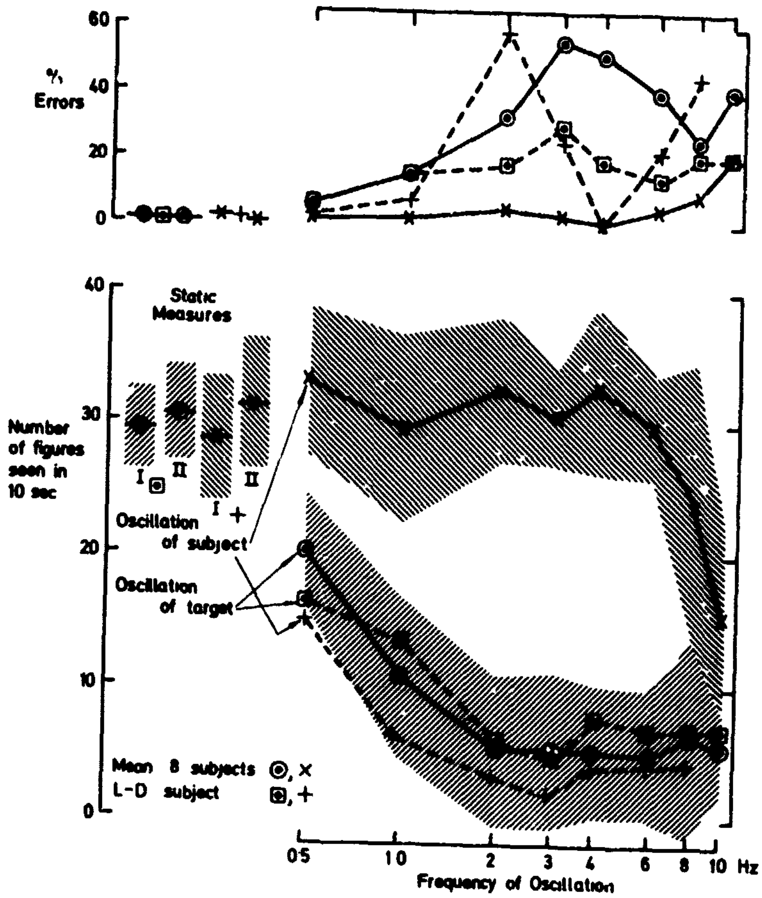

Fig. 1

Comparison of reading performance during sinusoidal angular oscillation in yaw of the observer (x) or of the target (O). Hatched areas represent ±1 S.D. The performance of a subject without functioning labyrinths (L-D subject) (+,□) indicates the importance of the vestibulo-ocular reflex during oscillation of the subject.

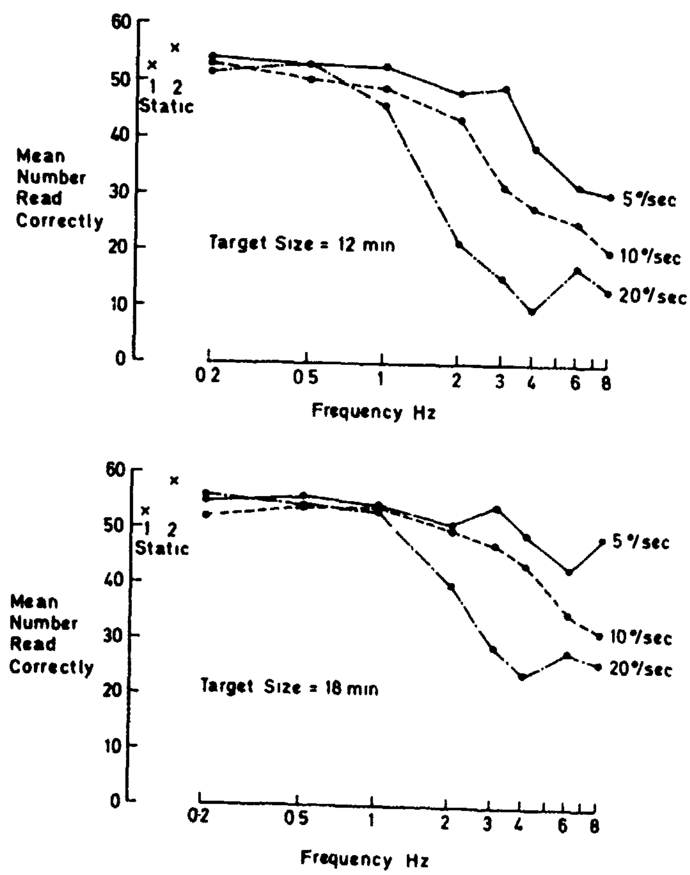

Fig. 2

Reading performance of a head-fixed display during angular oscillation of the head about the yaw axis at three levels of peak angular velocity (5,10 & 20°/s). Performance is based on number of digits read correctly during a 30 sec period; crosses represent calibrations without motion at beginning and end of run.

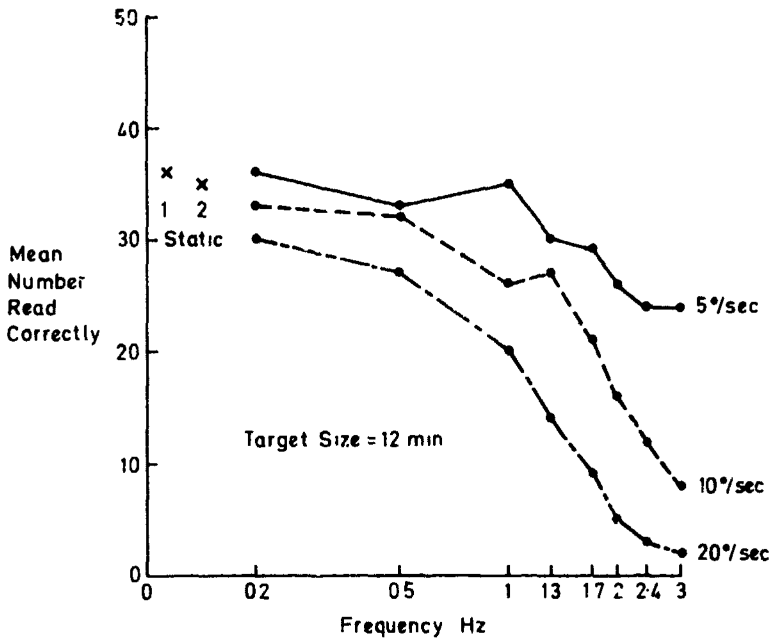

Fig. 3 Reading performance of a head-fixed display during angular oscillation of the head about the pitch axis at three levels of peak angular velocity (5, 10 & 20°/s). Performance is based on number of digits read correctly during 20 sec period; crosses represent calibrations without motion at beginning and end of run.

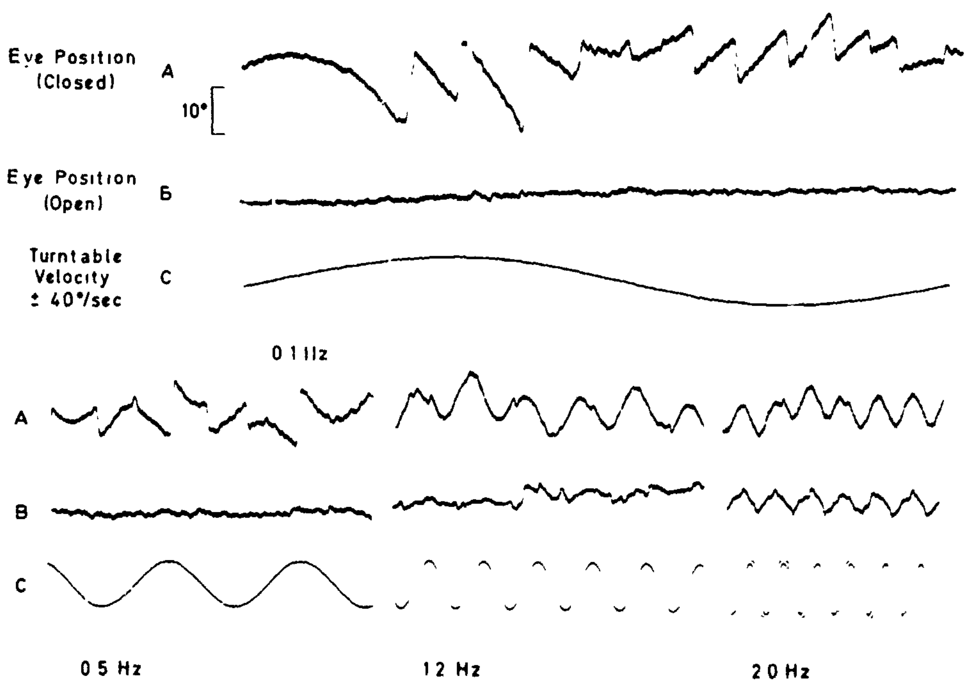

Fig. 4 Oculomotor response during angular oscillation of the head about the yaw axis at various frequencies in two conditions; (A) with eyes closed; and (B) with eyes open attempting to read a head-fixed display.

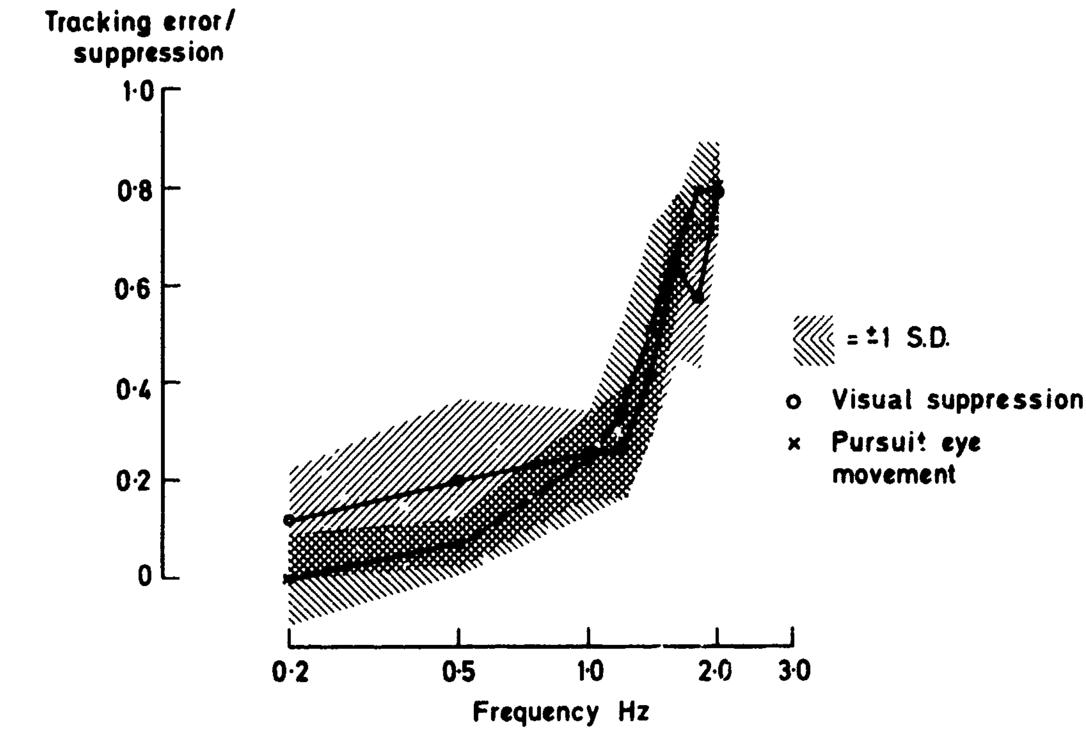

Fig. 5 A comparison of the frequency response of the pursuit reflex with that of suppression of the vestibulo-ocular reflex in similar experimental conditions. Suppression is defined as the ratio between eye velocities in the 'eyes open' and 'eyes closed' conditions. Tracking error is defined as the error between eye velocity and target velocity during target following in the horizontal plane.

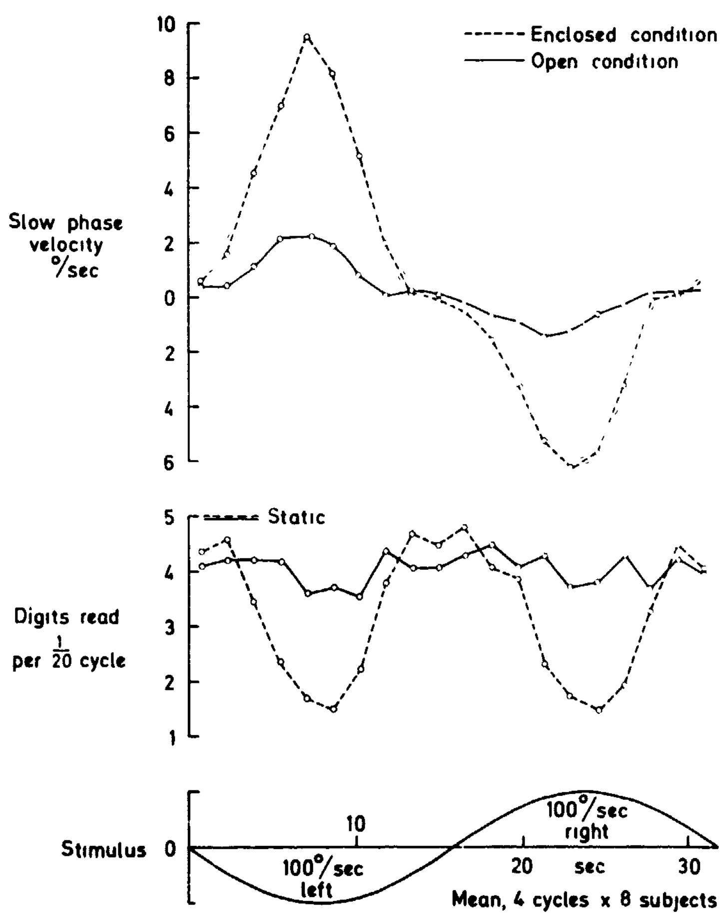

Fig. 6

The slow phase eye velocity and associated reading performance during sinusoidal angular oscillation at 0.3 Hz (peak velocity ±100°/s) when attempting to read a head-fixed display in two conditions - (a) enclosed and (b) open, viewing the stationary structured background.

impairment in reading speed and accuracy with respect to the static measures. At 2 Hz, reading speed had fallen to about 10% of the control level and there was no significant improvement at higher frequencies.

In contrast, the ability of the vestibulo-ocular reflex to stabilize the eye during head movement appears to be maintained at frequencies up to 9-10 Hz. The results shown in fig. 1 were obtained using the same display material described above, though in this experimental condition it was the subject who was exposed to sinusoidal oscillation in yaw (peak velocity ±30°/s) while viewing the stationary digit matrix. Statistical analysis of the measures of performance showed that a significant decrement did not occur until 10 Hz. It should be borne in mind that the digit size used in this experiment is close to the limit of static visual acuity, so that it is not surprising that a rapid breakdown was observed during pursuit. On the other hand the results obtained during head movement serve to emphasise the effectiveness of the vestibulo-ocular reflex in stabilizing the eye in the frequency range (1-10 Hz) where the pursuit reflex is largely ineffective. This feature is of importance during natural high frequency body movements, such as occur during walking and running. Subjects without functioning vestibular apparatus experience difficulty in maintaining visual acuity during such manoeuvres (see fig. 1). Fortuitously, modern man also finds this feature of great assistance during vehicular travel, where frequencies of stimulation are often well above the frequency range of the pursuit reflex.

SUPPRESSION OF THE VESTIBULO-OCULAR REFLEX

The problem is, of course, different when one considers the ability of the occupant of a vibrating vehicle to see an object which moves with his head as, for example, a head-mounted display. Eye movements, compensatory to the head motion, are no longer required, so the vestibulo-ocular responses must be suppressed if visual acuity is not to be impaired.

The ability of subjects to read a display which moved with the head during sinusoidal angular oscillation in yaw was assessed in an experiment (8), the results of which are summarised in fig. 2. The subject's task was to read a display of 3-digit random numbers generated electronically; the luminance of the digits was 85 cd/m^2. Both the subject's head and the display were rigidly clamped to the turntable structure. The measures of visual performance, expressed as the mean number of digits read correctly in a 30-s period (fig. 2), showed a significant decrement above a certain break frequency, which was positively correlated with digit size and inversely correlated with the peak angular velocity of the stimulus. Break frequency varied from about 0.5 Hz (±20°/s stimulus, digit height 12 min arc) to 3 Hz (±5°/s stimulus, digit height 18 min arc). A similar impairment of visual performance with frequency was also found when the subject and display were oscillated in pitch (fig. 3) though, in this configuration, the decrement developed more rapidly and could be detected at a slightly lower frequency (for a given target size and stimulus intensity) than when the angular vibration was in the yaw axis.

In another experiment with the same display, measurement of the lateral eye movements produced by an angular oscillation in yaw having a peak velocity of ±40°/s, revealed that at low frequencies ($<$0.5 Hz) the vestibular nystagmus was effectively suppressed when the subject fixated on the display (fig. 4). At higher frequencies, however, there was a progressive failure of suppression, such that at 2 Hz the amplitude of the eye movement, when the subject attempted to fixate, was only some 20% less than when he closed his eyes and there was no visual feedback. The breakdown in suppression was found to have gain/frequency characteristics very similar to those of the oculomotor control system responsible for target pursuit (fig. 5). This suggests that the mechanism for suppressing the eye movements engendered by vestibular afferents is similar to, if not the same as, that subserving the pursuit reflex.

THE EFFECTS OF BACKGROUND STRUCTURE ON VISUAL SUPPRESSION

Although the velocity and frequency of the stimulus to the vestibular system modifies the ability to suppress reflex eye movements, evidence has recently come to light that the nature of the stationary background is also an important factor. Results from an experiment by Benson and Cline (9) indicated that the ability to suppress could be greatly enhanced if the subject was able to see the surrounding static environment.

The experimental conditions were similar to those described in the previous experiment. However, in order to assess the effects of eye velocity without the confounding effects of frequency, the stimulus was a low frequency (0.03 Hz) high velocity (±100°/s) sinusoidal oscillation. The ability to suppress inappropriate reflex eye movements was assessed in two conditions: first with the subject and display enclosed in a light-tight compartment which moved with the turntable, as in previous experiments; and second, with the subject able to view the display against the background of the stationary room. Luminance levels of both display and background were maintained constant in both conditions. The subject was given a reading task similar to that used in previous experiments and eye movements were also recorded simultaneously.

The results, shown in fig. 6, showed quite clearly that the slow-phase velocity of unsuppressed reflex eye movements was significantly greater when the subject was enclosed and had no information about the static background. Associated with the increased eye movement was a decrease in the number of digits read during the same period, and subjectively there was greater difficulty in reading the display because of smearing of the retinal image. In a further experiment it was shown that restricting the field of view of the static room down to as little as 10° made the problem of suppression progressively more difficult.

These effects of background information on visual suppression have recently been substantiated by Guedry et al (10), although their experiments clearly point out the complexity of the relationship between peripheral visual motion cues and suppression of the vestibulo-ocular response.

THE EFFECT OF IMAGE VELOCITY ACROSS THE RETINA ON VISUAL ACUITY

When there is relative movement between the eye and a visual display, as there is when attempting to suppress inappropriate reflex eye movements, the image of the retina becomes smeared and there is a consequent decrement in visual acuity. Miller and Ludvigh (11) showed that when a subject attempts to track a moving object, the ability to discriminate the visual detail becomes impaired at high levels of target

velocity. They showed that the so-called 'dynamic visual acuity' obeyed a cubic relationship with target velocity, falling off sharply at velocities in excess of 40-60°/s. They suggested that this effect was the result of velocity errors in the tracking process. However, it is difficult to measure the instantaneous velocity error in such conditions and relate it to the decrement in visual acuity. An alternative approach was adopted in the following experiment (12), in which an attempt was made to examine the effects of image motion across the stationary retina on visual performance.

The subject viewed a display which was a horizontal array of 3 seven-segment red LED digits viewed against a superimposed static background. The display was attached to a rotating platform which permitted translational movement of the display at a predetermined constant velocity in the horizontal plane. In order to eliminate tracking movements of the eyes, the subject was prevented from seeing the movement of the platform and the velocity and direction of movement were randomised to avoid prediction. To ensure foveal presentation of the display the subject viewed a fixation point indicating the position of display presentation which was extinguished as the display was illuminated. Recordings of eye movements, using electro-oculography and an infra-red camera, indicated no detectable eye movement up to 200 msec after presentation but it was decided to restrict exposure time to 80 msec to ensure stationarity of the retina. The task was to read the digits of the display as they flashed past the field of view.

Visual performance was assessed as the probability of correct detection of the digits of the display as a function of the direction and velocity of target motion. Fig. 7 shows the effect of image velocity on the probability of correct detection for 10,20, 40 and 80 msec exposures of the display. Subjectively it was considerably easier to read the digits during the shortest exposure since there was less smearing of the retinal image. This is reflected by the probability of correct detection, which fell off more steeply as a function of velocity for the longer exposures. It was found that the equation for a Gaussian distribution could be fitted to individual results with a high level of probability, which enabled performance to be identified by the velocity at which a particular percentage of the digits was read correctly.

In fig. 8 the velocity level for 90% correct detection (V_{90}) was selected as the dependent variable. Digit luminance was 8 cd/m^2 and there were 5 levels of contrast from 1 to 16. Digit height was 18 min arc, so that the width of each LED segment subtended approximately 3 min arc, and the fundamental spatial frequency was approximately 6 cycles/deg. Fig. 8 shows that the display could be seen at significantly higher velocities for the briefest exposure than for the longer exposures, but there was no significant difference in the V_{90} value for 40 and 80 ms exposures. The effect of increasing contrast was to increase the velocity level for the brief exposure but there was no effect with the longer exposures.

It is of interest to consider the origin of these effects. The effect of the experimental procedure was similar to that involved in varying the duration of exposure of a photographic film except that, of course, the film is irreversibly modified, whereas the retinal image decays with time. Thus the trail left by the moving image is not of constant density, as in a film, but decays like the image on a CRT with a medium persistence phosphor. The temporal modulation transfer characteristics of the visual system suggest that the time constant of decay is approximately 10 msec, so that after 40 msec the response will have decayed to 1 or 2% of its peak value. The trail left by the image is thus virtually complete and any further exposure will not increase the problem of detection. Therefore it is not surprising to find no significant difference in the performance at 40 and 80 msec, and it may be predicted with some confidence that the values of velocity obtained can be used for the assessment of performance during continuous exposures, provided that the relative velocity between the eye and the viewed object is known.

As the velocity of the image increases, the trail will increase in breadth and tend to fill the spaces between the LED segments. Thus the problem of detecting the form of the image becomes one of detecting differences in contrast within the smeared trail and not of comparing the image with the background. Consequently it is not surprising that there was no effect of background contrast on the performance at 40 and 80 msec. On the other hand, during the briefest exposure the trail left by the image is abruptly cut off before it becomes fully developed and so there is a well defined contrast edge to be compared with the background. Hence, contrast with the background has a significant effect on the velocity level at which the display can be seen.

The effects of digit luminance on visual performance were also investigated at levels of 0.5, 2 and 8 cd/m^2. The velocity level for 90% correct detection (V_{90}) increased with digit luminance in a monotonic and significant manner (fig. 9). At these levels of illumination the responses correspond to those obtained for the modulation transfer characteristics of the eye, where increasing luminance increases the contrast sensitivity. Since the contrast is inversely related to image velocity, higher levels of velocity are achieved for increased luminance. We might expect this effect to disappear at higher luminance levels when the ratio of contrast sensitivity to background luminance becomes fairly constant. On the other hand, the temporal modulation transfer characteristics of the eye indicate that the image decays more quickly at higher luminance levels so that the problems of image smear may become less when viewing a bright display and/or background.

In an attempt to make some correlation with measures of acuity, the effects of digit size on performance were also investigated, the results of which are shown in fig. 10. There was an apparently linear relationship between velocity for 90% correction detection and digit size. This is not unexpected since the form of the image trail should be similar for a target of height 12 min arc moving at 2°/s and one of 24 min arc moving at 4°/s, although there is a difference in the spatial frequency of the display which may modify the response to a certain extent.

Thus, it may be concluded that the decrement in visual acuity for a target moving across the fovea of a stationary retina is largely brought about by the decrease in contrast between elements of the display and by the extent of image overlay, features which are dependent upon the temporal decay characteristics of the smeared retinal image. The results indicate that there is a 90% probability of correctly reading the display (digit height 18 min arc) if the image velocity across the retina does not exceed approximately 3°/s. The results, discussed above, of experiments on suppression of the vestibulo-ocular reflex (figs. 2 & 3) indicate that at frequencies between approximately 2 and 10 Hz eye velocity was greater than 3°/s for at least part of the cycle. This enables an explanation to be given for the occurrence of the nodal

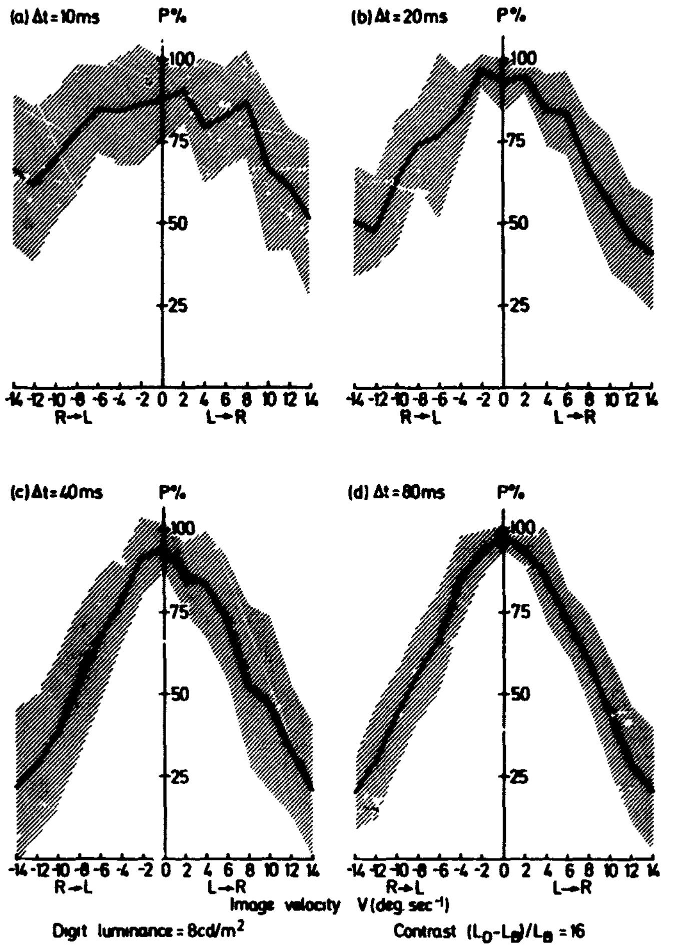

Fig. 7

The effect of image velocity (V) on the percentage number (P) of digits read correctly for different durations of display presentation (Δt) (Mean of 8 S's ±1 S.D.).

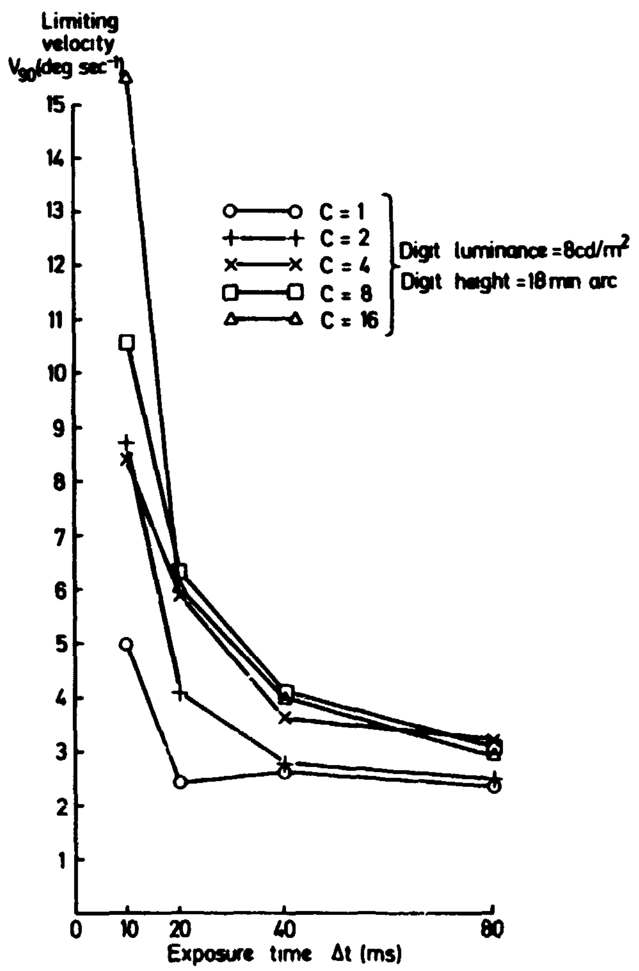

Fig. 8

The effect of display presentation time (Δt) on the limiting velocity for 90% correct detection (V_{90}) for different contrast levels (C). (Mean of 2 S's).

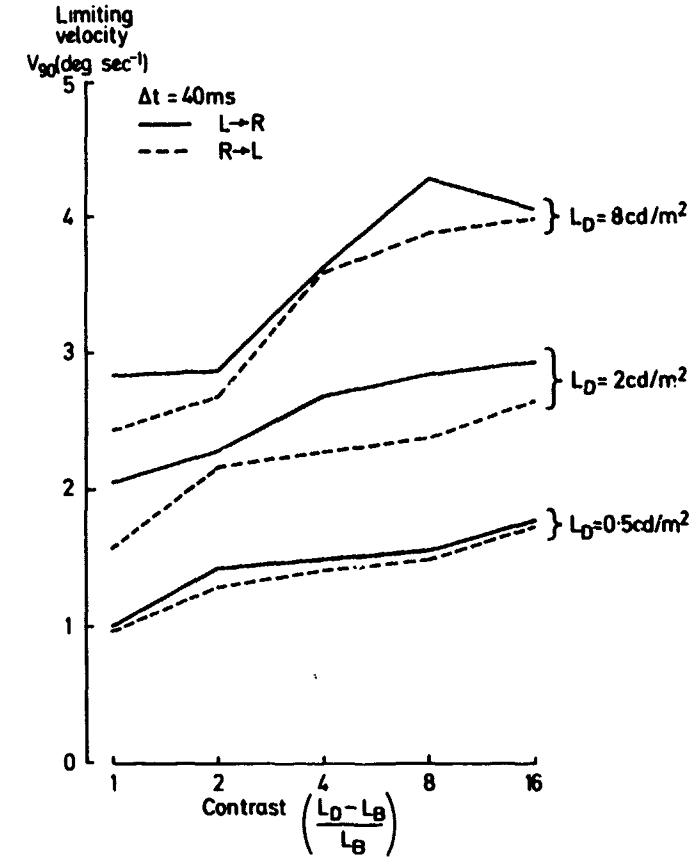

Fig. 9

The effect of contrast on the limiting velocity (V_{90}) for 90% correct detection at 3 levels of digit luminance (L_D). Display presentation time (Δt) = 40 ms.

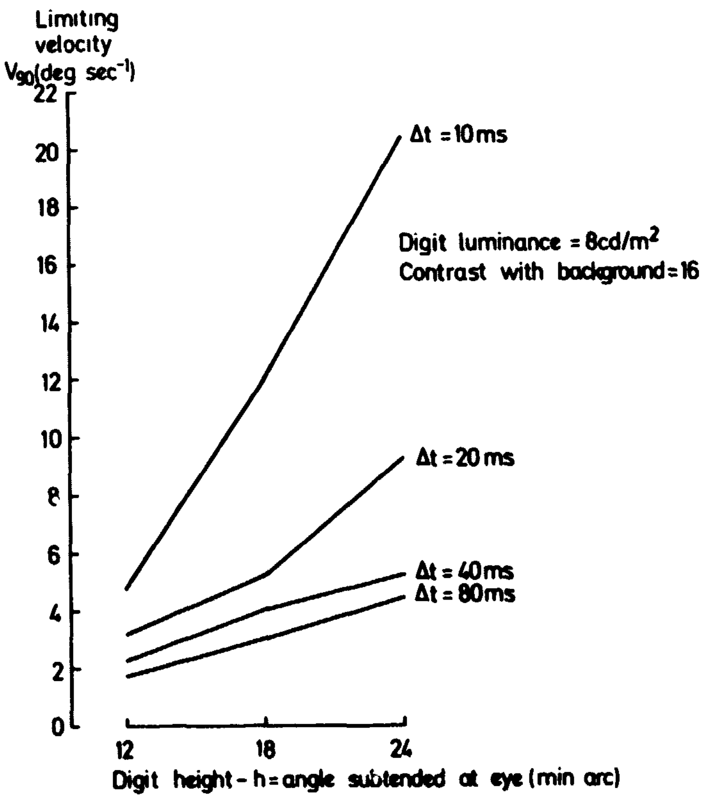

Fig. 10

The effect of digit height (h) on the limiting velocity for 90% correct detection (V_{90}) for different display presentation times (Δt).

images observed during the low velocity periods of a sinusoidal image movement.

The relationship between eye velocity and visual acuity has been assessed by Guedry (13) during attempts to suppress inappropriate reflex eye movements resulting from a transient stimulus to the vestibular system. Eye velocity was measured at the instant when the subject reported the ability to read clearly characters of a particular size from a range of character heights. There was considerable variation in subject performance, but on average the eye velocity levels at which digits of height 12, 18 and 24 min of arc could be seen were approximately 5,9 and 12°/s respectively. These velocity levels are some 2 to 3 times higher than those predicted for 90% correct detection from Fig. 8 and would correspond to a probability level for correct detection of approximately 50%. This is a rather low value, since the subjects were reporting the ability to read the characters correctly. However, the conditions of the two experiments were in many respects dissimilar and could account for this apparent discrepancy.

THE BIODYNAMIC RESPONSE OF THE HEAD

The crucial question to be answered here is whether the stimulus conditions which have been shown in the laboratory to produce significant decrement in visual acuity are likely to prevail in flight. Recordings of vertical and lateral acceleration within the cockpit have been obtained for several in-service aircraft and many of these indicate that during low-level high-speed flight acceleration levels of 2.5 m/s^2 RMS in heave and 1 m/s^2 RMS in sway may be expected in the frequency range 0.1 to 20 Hz. The head movement resulting from such vibration levels has been assessed by Rance (14). Subjects were exposed to either vertical or lateral sinusoidal oscillation at frequencies between 1 and 20 Hz with a peak acceleration level of ±3.9 m/s^2 (2.75 m/s^2 RMS), whilst seated without shoulder restraint on a hard seat. The angular acceleration of the head in pitch, yaw and roll was measured and, as the results in fig. 11 indicate, considerable angular movements were induced, that peaked between 4 and 10 Hz in all axes. Similar magnitudes of head angular acceleration were obtained in response to lateral vibration although the predominant activity was about the roll axis.

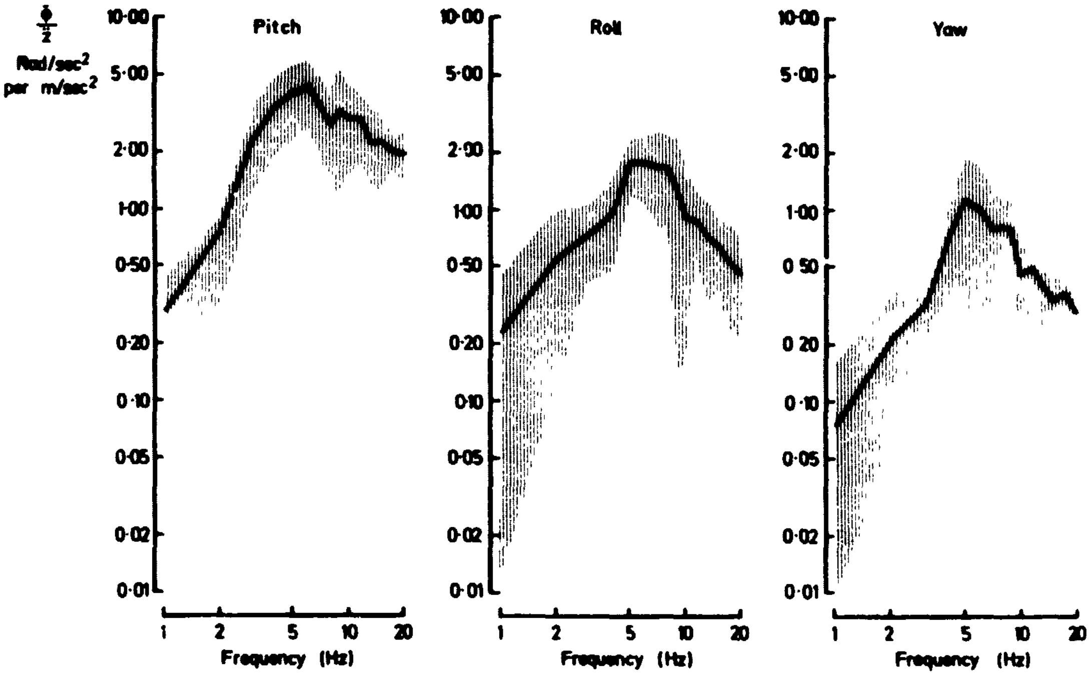

Fig. 11 The ratio of head acceleration ($\ddot{\phi}$) about the pitch, yaw and roll axes to linear acceleration ($\ddot{z}$) in the vertical axis of magnitude ±3.9 m/s^2 (Mean of 8 S's ±1 S.D.)

The responses may be translated into head angular velocity, yielding values of between 10 and 30°/s at frequencies between 1 and 10 Hz. The general form of the frequency response curve for head movement has been substantiated by results obtained during attempts to align a helmet-mounted sight with an earth-

fixed target (15). In these experiments the driving stimulus was provided simultaneously in the vertical and lateral axes by recordings of aircraft vibration in low-level high-speed flight. It is of interest that the visual feedback provided by attempts to align the helmet-mounted sight with a fixed target was unable to suppress the head movement to any appreciable extent.

DISCUSSION

The angular velocity of head movements found in these laboratory experiments indicate that there is likely to be a significant decrement in reading performance during aircraft vibration. The results of experiments on suppression of the vestibulo-ocular reflex (figs. 2 & 3) show that in the specific range of frequencies (1-10 Hz) in which there is the greatest transmission of acceleration to the head, it is difficult to suppress inappropriate eye movements. Hence, it is to be expected that the velocities of eye movement generated will reach peak values of similar magnitude to that of the head (i.e. $10\text{-}30^{\circ}/s$). Thus images projected from a head-fixed display will move across the retina at such velocity levels. The results of experiments on the detection of images moving across the retina (fig. 8) suggest that such velocity levels will be in excess of that required for 90% correct detection ($3^{\circ}/s$ for an 18 min arc digit).

It is difficult to predict the decrement in reading performance which is likely to result from the random head movements in flight given only the results of the experiments on visual suppression depicted in fig. 2, in which the stimulus was a sinusoidal waveform. As noted earlier, such a stimulus has regularly repeated periods of velocity which are within the band of $\pm 3^{\circ}/s$ required for 90% correct detection, leading to the presentation of degraded nodal images (16). In a random movement of the head (and thus of the retinal image) periods of low velocity would occur but in an unpredictable manner, making the task of image detection more difficult. It would seem that the probability of correct detection of a randomly moving image is likely to be a function of two factors: (a) the percentage of time for which the image velocity lies within the threshold levels (say $\pm 3^{\circ}/s$ for 90% correct detection) and (b) the time interval for which the image velocity lies within such threshold limits. Another important practical factor, which may override such considerations, is that the requirements of the observer to assimilate and possibly act upon the information received are likely to result in the visual material being assessed with a frequency which is less than that at which nodal image presentations appear. Experiments are currently being carried out in an attempt to assess the decrement in visual performance during random head movement.

Apart from the effects of head and eye velocity it is apparent from the experimental results presented here that other factors are very important in assessing the probable decrement in visual performance. Chief amongst these is the size of the elements of a display. The results presented in fig. 10 indicate that increasing the size of digits in a display increases the velocity at which they can be detected effectively. This is supported by the results of the visual suppression experiments (fig. 2), in which there was a significant improvement in performance when the digit height was increased from 12 to 18 min arc. However, if, as suggested earlier, this is a direct result of the image blur pattern produced by movement of the image across the retina, it might be expected that digit size, per se, was not the only critical factor. A decrease in the stroke-width to height ratio of the digits would lead to the blurred image trail filling less of the area between display elements and thus making the task of discrimination easier. Changes in the aspect ratio of display characters is also likely to modify visual performance for similar reasons.

A second important factor in assessing the relevance of the experimental results is the luminance of the display and the nature of the background against which it is viewed. In general, the brighter the display and the greater the contrast with the background the more easily it can be seen during movement although, in the experiments described here, the levels of illumination used do not approach those of the brightest conditions encountered in flight. Perhaps more important is the fact that the experimental results indicate that it is more difficult to achieve suppression when there is no structural stationary background against which to view the display. This may imply that it is more difficult to use a helmet-mounted display at night or when flying in cloud than when there is full visibility of the external world. Recent pilot experiments in the laboratory have indicated that this effect is most marked when using random movement stimuli, and it is intended that the effects of background contrast and structure shall be fully investigated in future experiments.

Finally, in all the preceding discussion on the decrease in visual performance, it has been assumed that the head movements induced by the appropriate stimuli in the laboratory are representative of those encountered in flight. However, there is little information about actual levels of head acceleration in flight. Thus an experiment is currently being planned in which angular head movements will be measured in various flight conditions. The results of this experiment should provide a more definitive indication of the accelerations to be expected and thus enable a better assessment of the effects of aircraft vibration on vision.

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THE EFFECT OF 3-25 Hz VIBRATION ON THE LEGIBILITY OF NUMERIC LIGHT EMITTING DIODE DISPLAYS

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SUMMARY

This paper describes the effects of 3-25 Hz sinusoidal vibration at an rms acceleration level of 2.5 m/s^2 in both the vertical and lateral axes on the performance of a reading task. The task was to read aloud numeric characters presented on a yellow high luminance light emitting diode display which had been designed for the military cockpit. Random numbers were presented on the display in sets of four changed every 3 s. The subjects were each fitted with a Mk 2/3 flying helmet and strapped into a Martin Baker Mk 10B ejection seat which was mounted on the same vibration platform as the display. Tests were conducted with the subject's head held both against and just off the head rest.

The results indicate that reading performance was affected most by lateral vibration, when the head was against the head rest. Maximum errors occurred for lateral vibration frequencies of 14-16 Hz which is shown to correspond to the probable onset of overlapping nodal images due to head vibration.

1 INTRODUCTION

It is a common observation that vibration can interfere with human activities particularly man's ability to observe quickly and accurately. In the past there have been many investigations into the effects of vibration on vision. However, such studies have largely been unrealistic in that the subject has been vibrated relative to a stationary display or vice-versa instead of both being vibrated together; also the seating conditions, vibrations and displays used have been non-representative of modern military aircraft. The tasks required of the modern military aircraft, such as terrain following, high speed low altitude flight in turbulence, or high speed helicopter flight, can impose a high degree of vibration on the pilot. This coupled with the higher pilot work load has made the choice of cockpit displays very important. In this experiment the effects of vibrations typical of modern aircraft on the readability of proposed future displays was studied using appropriate seating and aircrew equipment.

The choice of display used in these experiments was related to the need to replace conventional analogue pointer instruments in aircraft cockpits with modern displays having a multi-function capability. The advent of modern digital computers means that more data is potentially available to the pilot. Traditionally, much of this data would have been displayed on dedicated instruments in the cockpit. However there is not room for any more instruments and furthermore the pilot's work load is already high due, partly, to the excessive number of instruments and controls with which he has to deal. Multi-function displays therefore serve two purposes, firstly to reduce the number of controls and displays within the cockpit and secondly to reduce work load by displaying only the data immediately required by the pilot.

There are several modern display technologies suitable for displaying data in this way and it is likely that more than one type will be used in cockpits for the foreseeable future. Where a large quantity of data is to be displayed (for example video or graphic presentations) at present the cathode ray tube is the preferred technology, although prototype large area matrix displays are being developed. For displaying a small number of digits Light Emitting Diodes (LED) displays have many advantages. They are reliable, require low voltages (<10 volts), are of high luminance, are easily multiplexed and can be as legible as an ideal passive display over a wide range of incident illumination levels[1]. A range of LED displays designed specifically for use in high ambient illumination[2] has been developed and are to be installed in a variety of military aircraft in the near future. Such a display was used for these experiments.

2 EQUIPMENT

2.1 Vibration rig and seat

The vibration rig used was the RAE two-axis facility. This apparatus has a 1.83m × 1.32m platform which can be vibrated in the vertical axis and one horizontal axis. The frequency range of the rig is 0.5-50 Hz, within the limitations of a ±19.6 m/s^2. The seat used was a Martin Baker Mk 10B ejection seat mounted on the vibration platform (Fig 1) such that either vertical or lateral (g_z or g_y) acceleration could be applied.

The seat was fitted with a harness which was worn for all tests. The transmission of vibration to the head of a subject seated in such a seat has been fully reported elsewhere[3], and results are summarised in Fig 2 as plots of the ratio of head accelerations to lateral platform accelerations.

2.2 Visual display

The display shown in Fig 3 was a yellow (peak emission 580 nm) four character LED device, each character comprising seven segments with an overall height of 4 mm. Each segment of the display contained two light emitting diodes driven in series, and each character was refreshed at 1 kHz. The data for all four characters was entered via a paper tape reader and automatically changed every 3 s. The display was mounted rigidly on the vibration platform approximately 0.7 m in front of the subject and 10° below his horizontal line of sight.

Initially the luminance of the display was adjusted to a level which was considered and proved to give perfect legibility in non-vibrating conditions and this was subsequently measured to have an average luminous intensity of 0.38 mcd per character. The drive current was monitored throughout the experiments to ensure that the display luminance remained constant.

2.3 Ambient illumination equipment

The ambient illumination level during the main experiment was approximately 600 lx, generated by six normal 100W tungsten filament bulbs. The experimental arrangement is shown in Fig 1.

2.4 Subjects

Six male subjects who were either aircrew or well acquainted with vibration experiments were used in the main experiment. Each subject was fitted with a standard Mk 2/3 flying helmet and the ejection seat was adjusted for each individual to the correct back length. They were asked to tighten the seat harness as they would for flight and take up a typical posture but with their hands on their thighs and their head either lifted off or pushed against the head rest as instructed. It was emphasised that as far as they were able they should maintain harness tension and posture for all vibration and non-vibration runs.

Table 1 shows the ages, heights and weights of the subjects. All subjects had 6:6 vision or better, which was measured prior to the commencement of the experiments.

3 EXPERIMENTAL PROCEDURES

3.1 Vibration conditions

An unreported preliminary experiment was conducted to establish the vibration level to be used in the main experiment. The results indicated that in general, vibration levels below about 2.5 m/s^2 rms, were unlikely to affect visual performance. For the main experiment sinusoidal vibration of rms acceleration level 2.5 m/s^2 and frequencies 3, 5, 7, 10, 12, 14, 16, 18, 21, 23 and 25 Hz were therefore used in each of the vertical and lateral axes. Such vibration conditions are often encountered in helicopters; however, in fixed wing aircraft, although the vibration acceleration levels of 2.5 m/s^2 may be encountered in high speed low altitude flight, the frequency spectrum is rarely single frequency. Each subject repeated each test condition twice in one vibration session, once with his head held against and once with his head lifted off the head rest. The twenty-two vibration conditions of one session were presented to the subjects in a random order. Three subjects (3, 4, 5) completed three sessions and three subjects (1, 2, 6), only two sessions (owing to subject availability). Each vibration condition was repeated three and two times respectively in each of the vertical and lateral axes.

3.2 Visual task

The subject was asked to read aloud the numbers which were presented to him in sets of four. These were changed every 3 s. A total of 100 numbers (25 sets of 4) were presented as one run, which therefore lasted approximately 75 s. The visually presented data was randomised for each vibration condition. A complete test session of twenty-two runs therefore lasted approximately 30 min. Before each test session there was a period with and without vibration in which the subject could familiarise himself with the visual task, character format and the experimental environment. Reading error scores were recorded to check for any effects of fatigue and to ensure that the condition of 100% readability under no vibration was maintained.

4 RESULTS

4.1 Dependence of legibility upon frequency, mode of vibration and head position

The results of the main experiment are presented in graphical form in Fig 4. These graphs show the error rate for each subject for the range of frequencies used. The data are averaged over the repetitions of test conditions with both the head on and off the rest. However the variation of error rate between runs for each subject is relatively large and comparable with the variation seen in Fig 4 between subjects. To establish the performance of each individual with more certainty would have required a significantly

larger number of runs. In this situation the most reliable data is that averaged over all runs for all subjects, and this is given in Fig 5.

4.2 Legibility *vs* frequency

It can be seen that for vertical vibration for most subjects the maximum error rate was low (below 5%) when the head was either against or lifted off the rest. The distribution of errors with frequency was reasonably constant for all subjects.

For lateral vibration when the head was off the rest the maximum error rate was also below 5%. However with the head in contact with the rest the error rates for most subjects peaked in the region 14-16 Hz when the average error rates were considerably higher (up to 15% for subject 5). This peak is shown graphically in Fig 5 where data for all subjects is averaged and gives error rate as a function of frequency for each head position and mode of vibration.

It was conjectured that the increase in displacement of the head when against the rest may account for the increase in errors. Transmission ratio measurements had been made on subject 5, the subject who showed the increase in errors most strongly, as part of another investigation which is fully described in Ref 3. Head motion in each of the three linear head fixed axes was measured on a bite bar fitted with accelerometers. For a lateral vibration input head motion or transmission ratios in all axes were small (below 0.5) when the head was lifted off the rest. However when the head was against the rest the transmission ratios increased considerably in all axes and are shown in Fig 2.

This would seem to correspond with the increase in error when the head was against the rest. However, the increase in error rate around vibration frequencies 14-16 Hz was not obviously related to any peaks in the transmission ratios. Simple measurements of transmission ratio however may not accurately reflect changes in visual performance as these do not include effects due to phase differences between the subject's head and the vibration rig. This parameter was not measured during these investigations.

4.3 Distribution of errors among the digits

It is of interest, from a display designer's point of view, to know the distribution of errors within the digits 0 to 9 for the 7-bar format used. During analysis of the reading errors made, it was found that subjects occasionally transposed two numbers, for instance when 34 was displayed within a batch of four numbers these were read as 43. It was considered that even though these were genuine errors and were included in the other error data they would not be included in the error distribution matrices shown in Table 2.

This shows the total number of times an error has been made on a particular digit as a fraction of the total number of digits presented over all subjects and all test sessions. For clarity the error fractions have been scaled up by a factor of 10^4.

The table comprises an error matrix for both vertical and horizontal modes of vibration, the total error rate for each being 0.99% and 1.61% respectively.

During vertical axis vibration it can be seen from the matrix that 8 was the digit misread most frequently and it was most often misread as 0. The difference between digits 8 and 0 was of course the presence or absence of the centre segment of the character and it was interesting to note that while 8 was read as 0 on 0.22% of the occasions that it was presented, 0 was read as 8 on only 0.005% of occasions.

The observation was contrary to that found in earlier work[2] concerned with the legibility of this display under high ambient illumination but not under vibration where it was found that 0 was more often read as 8 than vice-versa by a factor of 2 to 3.

4.4 Spatial distribution of errors

During debriefing, the subjects stated that the display image during vibration was elliptical in form and consisted of multiple images, (both lateral and vertical), of the four characters which overlapped for some of the vibration conditions. It was proposed that since the images overlapped the errors per character might be greater for the second and third characters than for the outside characters. Results of an analysis of errors as a function of character position are shown in Table 3. It was clear that more errors occurred for characters two and three during lateral vibration and that this was the prime reason for the higher overall errors for lateral vibration. These findings should strongly influence display design, the implications being that the overlapping of nodal images which is determined by the character to character spacing is an extremely important parameter when the display must be viewed under relatively high levels of vibration. To further test the hypothesis that the display character spacing was too close for 14-16 Hz vibration conditions a brief experiment was conducted in which this spacing was artificially increased by illuminating only every other character. One subject was used but under the worst test condition (14 Hz, lateral vibration head on the rest) no reading errors were made. The character spacing achieved by illuminating every other character was 7.8 mm.

5 CONCLUSIONS

The results indicate that all variables studied in this equipment ; vibration, frequency and axis, whether the head was against or off the head rest and subjects, had

an effect on the magnitude of the error rates in reading a four character, 4mm LED numeric display.

During debriefing of subjects it became clear that there were several well defined effects which gave rise to errors. Firstly, the image of the display was elliptical in form which indicated that the motion of the head was in both the vertical and lateral directions for either single axis input vibration. These cross coupling components at the head (shown in Fig 2) resulted in a blurring of the vertical image both vertically and laterally.

Secondly, overlapping of nodal images during lateral vibration made the middle characters of the display more difficult to read compared with the end characters. Retinal nodal image displacement due to yaw and pitch motion of the head is a possible explanation for the peak in error rates at a vibration frequency of 14-16 Hz.

It may be concluded from the error rate data that as the distribution of errors within the digits is not constant over all the digits, the character fount used was not 'ideal'. However a different format would not have totally eliminated errors since subjects stated that under some conditions the display was extremely difficult to read due to blurring of the retinal image and it is felt that this contributed far more to the error rate than the format of the characters. The blurring reported by subjects may be reduced by increasing the character spacing. This has been shown to eliminate errors for the 4 mm character height using 7.8 mm character spacing and a vibration frequency of 14 Hz. It therefore may be possible to predict an optimum character spacing for a display to be used in any particular vibrating environment using measurements of head vibration and consideration of nodal images.

The results of this investigation indicate that over all vibration conditions used the average error rate for vertical axis vibration was about 1% and for lateral vibration was 1.6%, although errors of up to 10% and 15% respectively were obtained under some vibration conditions. It should be noted that these high error rates were found for subjects only when the head was against the head rest. This is an unnatural posture and would normally only be adopted when flying sustained high acceleration manoeuvres, and then for a limited time. With this in mind, these results are very encouraging and indicate that such displays may be successfully employed in vibrating environments. However performance in a combined high illumination and vibration environment which may prevail in an aircraft cockpit has not been investigated. During vibration the retinal nodal images will be of a reduced luminance compared with the display when static and therefore to achieve the same luminance of the nodal images the display brightness may have to be increased when viewed in conditions of vibration.

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Table 1

SUBJECT DATA

Subject number	Age	Height (m)	Weight (kg)
1	35	1.72	73
2	38	1.77	74
3	40	1.78	73
4	29	1.83	70
5	40	1.79	61.2
6	31	1.87	86

Table 2

DISTRIBUTION OF ERRORS AMONG THE DIGITS

Vertical vibration

True

READ AS	1	2	3	4	5	6	7	8	9	0	∑
1	0	0.8	1.3	1.0	0.3	1.0	1.0	0.8	0.3	0.8	7.3
2	0.3	0	0	0	0.3	0	0.8	0.8	0.8	0.3	3.3
3	0	0.8	0	0	1.0	0.3	0	2.5	0.3	0.3	5.2
4	0.5	0	0.3	0	5.0	4.8	3.8	1.0	3.8	0.5	19.7
5	0	0.5	0.3	0.8	0	0.5	2.3	0.3	0.3	0	5.0
6	0	0.3	0	0	2.0	0	0	2.5	0	0	4.8
7	0.5	0	0	1.0	0.3	0	0	0.5	4.3	0.8	7.4
8	0	0	1.0	0	0	0.3	0	0	2.8	0.5	4.6
9	0	0	1.5	1.3	0.5	0	0.8	1.0	0	0	5.1
0	4.3	3.0	3.8	0.5	2.3	0.5	0	21.9	0.3	0	36.6
∑	5.6	5.4	8.2	4.6	11.7	7.4	8.7	31.3	12.9	3.2	99.0

Total error = 0.99%

Lateral vibration

True

READ AS	1	2	3	4	5	6	7	8	9	0	∑
1	0	0.3	2.3	1.3	0	0.5	5.0	1.5	0	0.8	11.7
2	1.0	0	2.5	0.3	0	1.5	1.3	1.5	1.0	0.8	9.9
3	0.8	3.8	0	0.3	2.3	0.3	3.0	4.5	0.5	0	15.5
4	0.8	0.3	0.8	0	6.1	6.1	2.8	1.3	8.3	1.0	27.5
5	0.5	1.0	1.8	0.8	0	1.0	1.5	0.8	0.5	0.3	9.2
6	0.3	0.8	0.8	0.3	1.8	0	0	4.5	0.3	1.0	9.8
7	1.8	0.8	2.8	0.3	0.3	0	0	0.3	5.0	0.3	11.6
8	0	2.0	4.3	1.0	1.8	5.0	0	0	3.8	4.0	21.9
9	2.0	0	2.5	5.8	3.5	0.3	2.5	2.0	0	0.8	19.4
0	5.0	3.5	1.8	0.5	1.8	1.3	0.8	9.8	0	0	24.5
∑	12.2	12.5	19.6	10.6	17.6	16.0	16.9	26.2	20.0	9.0	161.0

Total error = 1.61%

This table gives the total number of times an error has been made on a particular digit as a fraction of the total number of digits presented over all subjects and test conditions. Error fractions are scaled up by a factor of 10^4. Worst confusions underlined (error rate > 2×10^{-4}).

Table 3

DISTRIBUTION OF ERRORS WITH CHARACTER POSITION

Lateral vibration

	Left			Right
Character	1	2	3	4
Total number of errors	106	239	223	110

Vertical vibration

	Left			Right
Character	1	2	3	4
Total number of errors	97	127	102	97

All subjects - all experimental conditions

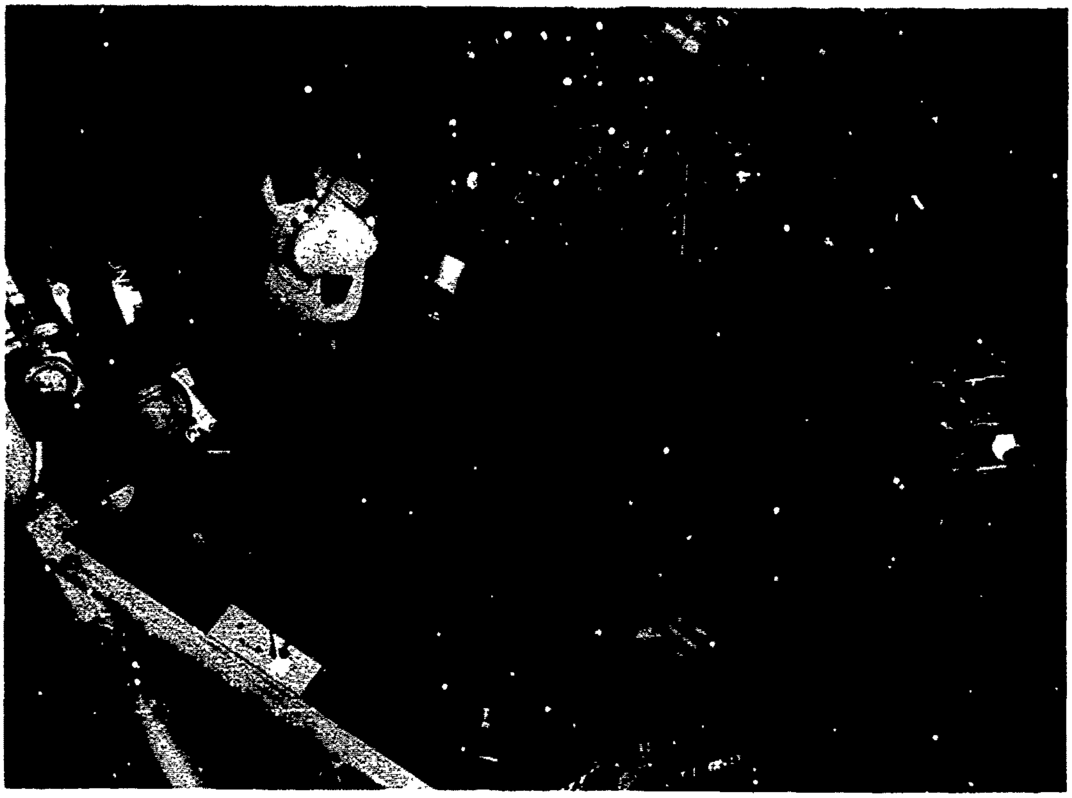

Fig 1 The equipment used in the experiments

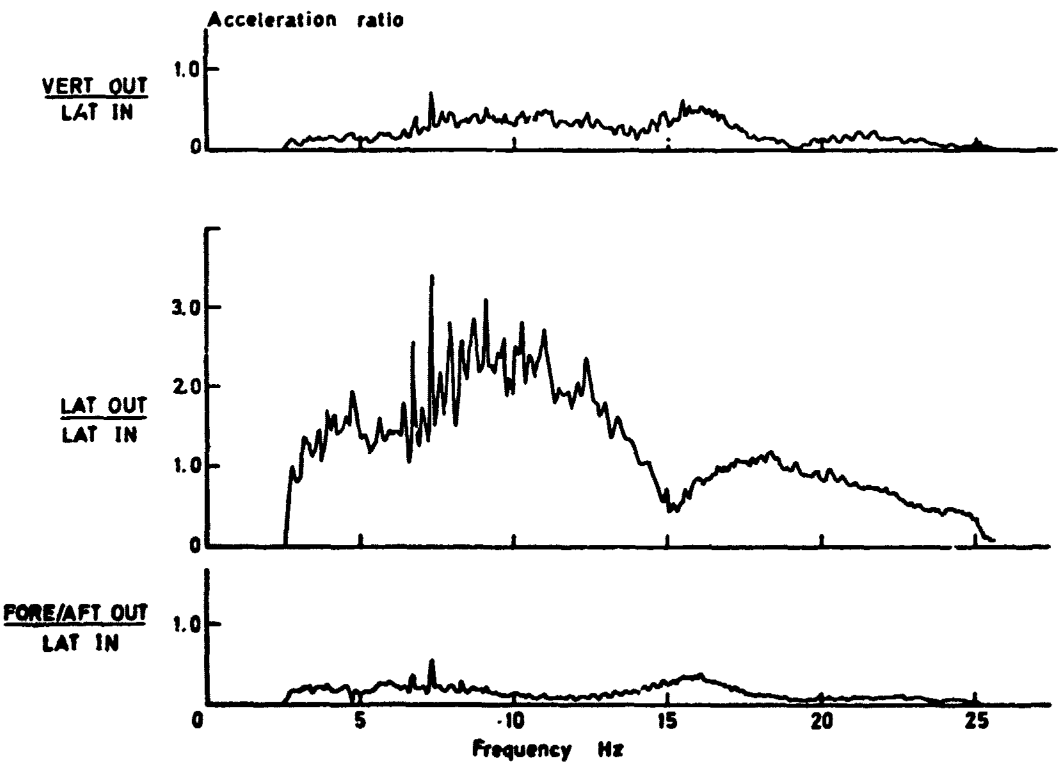

Fig 2 Mk 10B ejection seat. Transmission of linear axes vibration to the head - subject 5, head on rest lateral input vibration 3 ms^{-2} rms

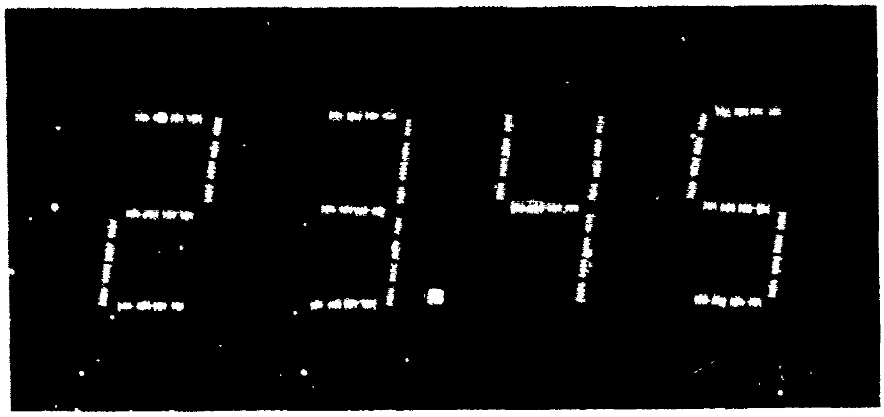

Fig 3 The display used in the experiments

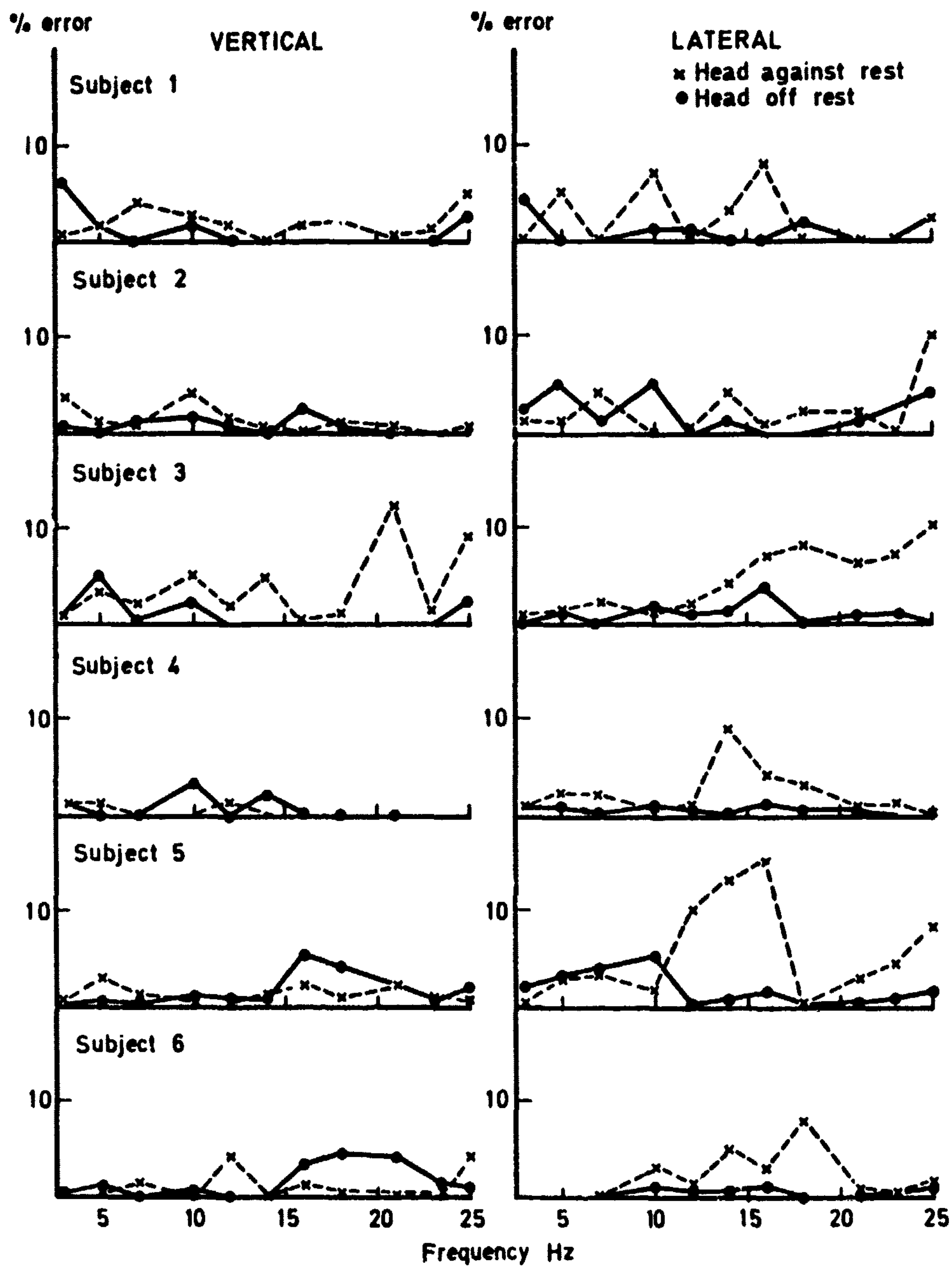

Fig 4 Average percentage error rate for each subject under all vibration conditions

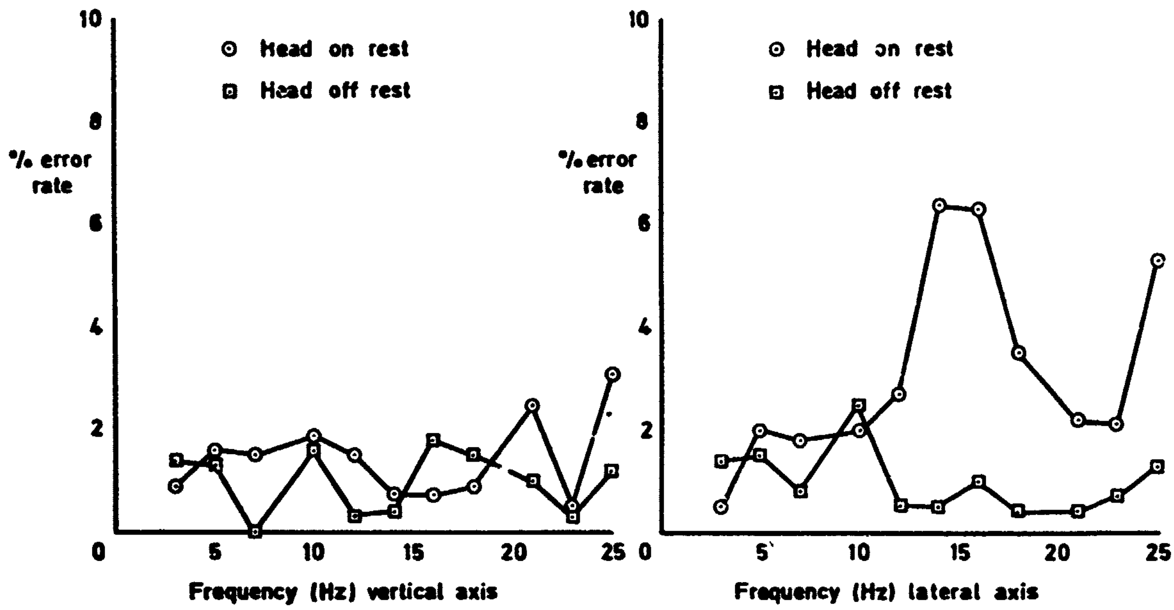

Fig 5 Error rate averaged over six subjects

DISCUSSION

DR. L. VOGT (FRG)

Referring to your slide which shows an increase in reading error around 14 Hz with lateral vibration and the head on the headrest (*figure 5 of text*) and which you said you could not explain. Have you looked into the dynamics of the head helmet headrest system to see if there is a resonance there?

AUTHOR'S REPLY

We have measured the vibration transmissibility of the subject wearing all the experimental equipment. The transmissibility of a single subject measured in all three linear axes has been analysed, but has not shown any peak in response at 14 Hz. There may, however, be something in roll or yaw which is giving rise to this increase in error rate.

THE EFFECT OF TURBULENCE ON HELMET MOUNTED SIGHT AIMING ACCURACIES

by

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SUMMARY

This paper describes some measurements that were made to assess the effects of the turbulence associated with high-speed, low-level flight on the accuracies achievable with helmet mounted sighting equipment. Experiments were conducted both in flight, during trials in a Canberra aircraft, flying straight and level at 350 kn, 250 ft, and in the laboratory, using a two-axis vibration rig driven by vibration data recorded from the same Canberra aircraft to provide simulated turbulence. The sighting equipment used was a Honeywell MOVTAS helmet mounted sight, which presented an aiming reticle in front of the wearer's right eye while helmet attitude angles were measured by optical sensing devices mounted on the outside of the helmet.

Aiming accuracies were obtained for collimated targets fixed in space in the simulation, and for both collimated targets fixed to the airframe and ground targets in flight. The results obtained show a good correlation between aiming errors achieved in flight and those obtained from the simulation, and demonstrate that the aiming errors consist mainly of a low frequency random motion which increases with vibration level. In addition, various techniques were investigated to overcome the errors involved in order to enable fine aiming to be performed with the helmet sight.

INTRODUCTION

A programme of experiments has been carried out at the Royal Aircraft Establishment supported by British Aerospace Ltd to assess the capabilities of both helmet mounted sights and displays in high-speed, low-level flight. One important aspect of this work has been the measurement of the effect of the involuntary head motion caused by turbulent flight on the aiming performance with such devices. This paper summarises some of the data obtained during these experiments on the aiming performance with this sighting equipment and on some of the improvements that can be made to the basic system.

THE HELMET SIGHT

Head pointing angles were measured using a Honeywell MOVTAS helmet mounted sight. This device presents the wearer with an aiming reticle, which is reflected from the helmet visor into the right eye. The reticle consists of two concentric rings (50 mrad and 10 mrad diameter), centred on the sight line. This reticle image is collimated to infinity and represents the aiming sight line. Sensors mounted on the sides of the helmet detect rotating beams of infra-red radiation emitted by two units mounted in the cockpit (or on the vibration rig in the simulation). The sensor signals are decoded into helmet attitude angles by a computer and a continuous estimate of elevation and azimuth pointing angles are produced. Once harmonised to the aircraft system, this configuration of helmet sight was found to operate to an accuracy of about 2 mrad over the range of azimuth and elevation angles used.

THE LABORATORY SIMULATION

Experiments were performed using a two-axis (heave and sway) vibration rig to simulate the aircraft turbulence. The vibration rig was driven from accelerometer recordings taken during high-speed, low level flight of a Canberra aircraft. This aircraft was flown at 350 kn and 250 ft and gave a rougher ride than would be expected from more modern ground attack aircraft with higher wing loading. The vibration was filtered to remove any power below 0.5 Hz or above 25 Hz (the vibration rig response) and produced an rms vibration level of 0.25 g heave and 0.1 g sway. Details of the vibration spectrum are shown in Fig 1. Lower levels of vibration were produced by lowering the vibration rig transmissibility. Subjects were seated in an ejection seat on the vibration rig and were told to aim their helmet mounted sight at targets which were collimated to infinity and in fixed directions in space relative to them.

FLIGHT TRIALS

The helmet sight was also installed in a Canberra aircraft and used during high-speed, low-level flight trials. The flight trials program was designed to assess the performance of both the helmet sight and other equipment on the aircraft. The helmet sight was installed in the pilot's cockpit and was used to designate targets to other systems in the aircraft. For the purposes of these experiments, the output of the helmet sight was recorded during flight together with other aircraft data and later analysed on the ground to provide estimates of aiming accuracy. Two types of target were used. The first (experiment C1) was the aircraft gunsight which was fixed to the aircraft and hence had no motion relative to the aircraft. The second (experiment C2) were ground targets whose motion, relative to the pilot reflected the motion of the aircraft through the air. The aircraft was flown at 350 kn, 250 ft, straight and level over level terrain and aiming commenced at a range of 2-5 km from the ground targets.

AIMING ACCURACIES

Aiming accuracies with the helmet sight against stationary targets were measured in the laboratory for a variety of vibration levels and a limited number of subjects. The rms aiming error for each 10 second aiming run was calculated and correlated with the input vibration level. The linear regression lines are shown in Fig 2 (elevation head motion versus heave vibration) and Fig 3 (azimuth head motion versus sway vibration). The amount of head motion varied from almost none under no vibration (head motion lost in system noise) to up to 30 mrad elevation error and 16 mrad azimuth error under the highest vibration level, although it must be remembered that the vibration levels are higher in the Canberra aircraft than in more modern aircraft and that this highest vibration level was rated as severe turbulence.

Also shown on these two graphs are the results from the flight trials. The regression lines from the fixed target aiming are labelled C1 while the lines for ground target aiming are labelled C2. As can be seen, agreement with the laboratory data is good except for the C2 azimuth error. This azimuth aiming error results from the additional target motion in experiment C2. The Canberra aircraft at high-speed, low-level tends to produce a snaking motion in yaw, causing an effective target motion in azimuth and tracking this target motion causes aiming errors additional to those for the fixed targets.

Frequency analysis of the helmet sight output was also performed and Fig 4 shows the power spectra of tracking error (*ie* the involuntary motion) for a typical run. This graph shows that the bulk of the power occurs at low frequencies, less than about 4 Hz, while higher frequencies present in the vibration input are damped out by the human body.

IMPROVEMENT TECHNIQUES

Aiming errors of this magnitude limit the usefulness of helmet mounted sighting equipment. Although these errors are, perhaps, adequate for coarse weapon aiming, somewhat improved errors are required for fine aiming of some weapons. Some attempt was made therefore to find a technique to improve on these errors.

The first improvement technique which was applied is that of filtering the data. Since the output of the turbulent helmet motion is a continuous signal, filtering (analogue or digital) can remove the higher frequency oscillations, leaving only the low frequency information. This process is identical to that of time averaging the data. By averaging over 1 second, say, noise with frequencies greater than 1 Hz is removed, leaving only the effective mean aiming point. The drawback of this method is that, for a 1 second averaging period, a 1 second lag is put into the system, which may be unacceptable, and also, reliance is put on the subject maintaining his aim for the whole of that second. A few simple filtering techniques were performed during these experiments, which indeed showed a decrease in error of more than 50% at the expense of response time, but insufficient trials were performed to quantitatively assess the method.

The second technique tried was to enable the pilot to mark the target instantaneously with an event button, when he thought he was aiming precisely on the target. At the instant of mark, the helmet sight output was used to compute the instantaneous aiming error. This experiment was performed in the laboratory and the results are shown in Table 1, for three different vibration conditions. Both instantaneous marking errors and rms tracking errors over 10 seconds of tracking per run are shown, each averaged over a number of runs. As can be seen the marking accuracies are very comparable with the tracking accuracies suggesting that no improvement can be made by this method. The conclusion is that marking accuracy is equivalent to a random sample of the involuntary head motion, a fact not wholly unexpected since the head motions contain higher frequencies than the bandwidth of the human headpointing control system.

The third method of improvement, the most complicated, involves a scaling of the output of the helmet sight. By scaling down the helmet sight output, a greater signal to noise ratio can be achieved between the voluntary head aiming motion and the involuntary head turbulent motion. Unfortunately, since there is no longer a one-to-one correspondence between head attitude angles and spatial aiming angles, the helmet sight reticle can no longer be used as an indicator of the aim point. Instead, visual feedback must be given by a display of the aiming process presented on a display surface (head-down, head-up or even helmet-mounted). The process, therefore, links best with a sensor, and consists of providing the subject with a display from the sensor showing the target and an aiming cursor; the helmet sight is then used in place of the more conventional hand controller. The position of the cursor is controlled totally by the pilot's head position while he looks at the display. For a scaling of 10:1, a 100 mrad head movement will result in a 10 mrad (visual angle) cursor movement, while a 10 mrad involuntary head motion will be scaled to a 1 mrad cursor movement, etc. An initial course aiming process is required to acquire the target onto the display and establish the origin for the subsequent helmet control inputs. Some laboratory experimental data has been obtained on the efficiency of this technique. Experiments were performed of a full weapon aiming process of which this technique was a part. Static targets were presented using a Hughes helmet mounted display as the display surface. Aiming error under vibration (low-level Canberra in the laboratory) was extracted from the results of these experiments, and is summarized in Table 2. Scaling factors of 2:1, 4:1 and 10:1 only were used and only radial aiming error (median) was computed. These results, however, are not inconsistent with the results for the effective 1:1 scaling shown in Table 1. A clear improvement can be seen as the scale factor is increased, consistent with the effective decrease of the involuntary head motion component. Limits on the desirable total head movement, however, limit the effective coverage of the head as a controller in this mode, especially at the higher scaling factors.

A very quick test was also performed using the helmet sight as a rate controller with the cursor rate controlled by the subject's head position. The results obtained were encouraging, producing aiming errors similar to the 10:1 scaling case. This method has the advantage that the head movements can still remain small without limiting the coverage of the system.

This third improvement technique, therefore, appears to be an effective method of improving the aiming accuracy with the helmet sight, although it can only be used in those cases where the aiming process can be linked to a sensor or otherwise transferred to a display surface. However, if no such display is available, only the technique of filtering can be employed.

CONCLUSIONS

The major contribution to helmet sight aiming accuracy in high-speed, low-level flight is the involuntary head motion caused by the turbulence. This involuntary head motion consists of a low frequency random motion with a cut-off of 4 Hz and amplitude dependent on the vibration level. Filtering of the helmet sight output may be used to reduce the effects of this involuntary motion, while attempts to mark instants of more accurate aiming provide no improvement over random sampling of this involuntary motion. Use of a helmet sight as a control input to aiming tasks on a display shows promise, but this needs further investigation with specific applications in mind.

Table 1

Values in mrad		Vibration condition		
		None	Canberra	
			Low	High
Marking error (standard deviation over runs)	Azimuth	5	19	21
	Elevation	4	26	37
Rms tracking error (mean over runs)	Azimuth	4	16	19
	Elevation	4	30	33

Table 2

Scaling factor	2·1	4:1	10:1
Radial aiming error mrad (under Canberra vibration low level)	8	5	3

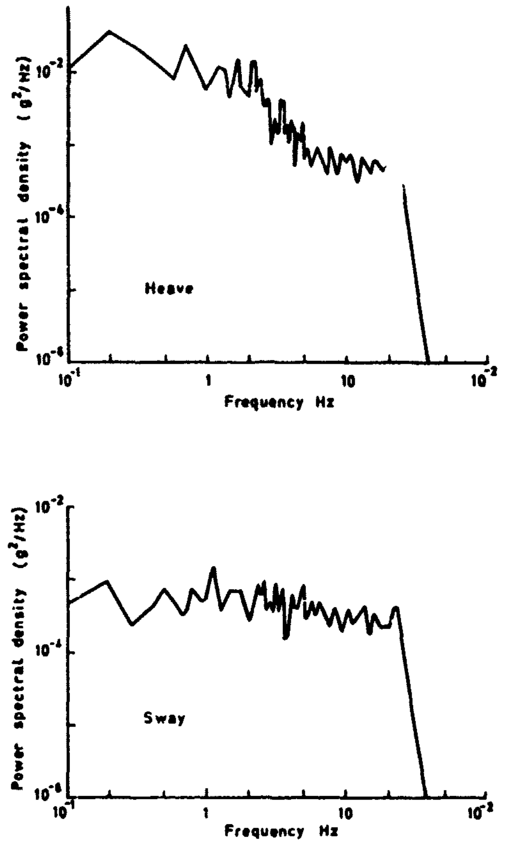

Fig 1 Details of the vibration spectrum

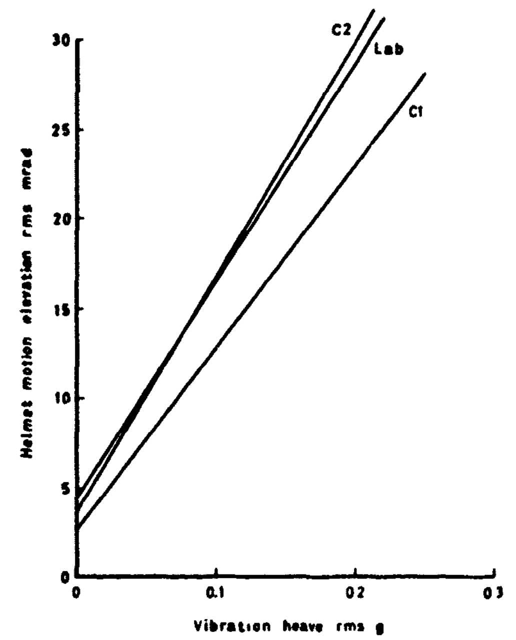

Fig 2 Elevation head motion regression lines

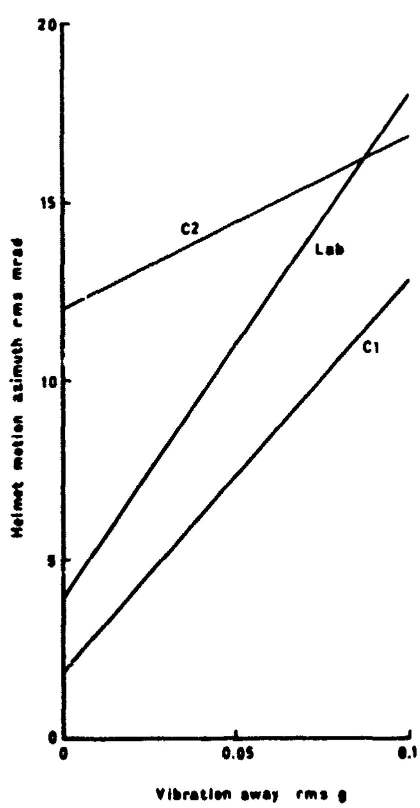

Fig 3 Azimuth head motion regression lines

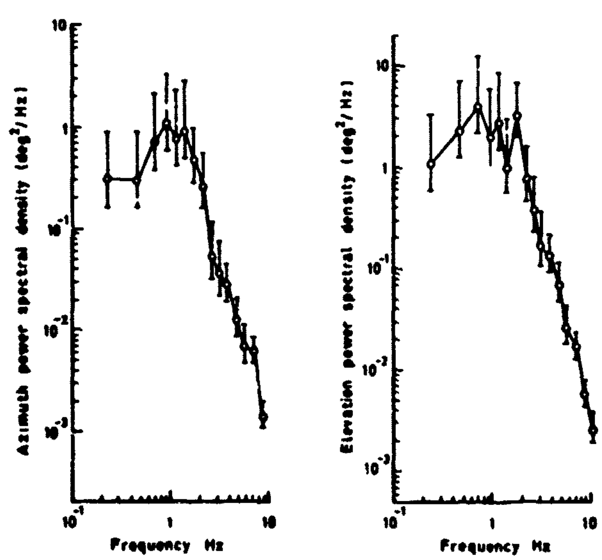

Fig 4 Power spectra of tracking error

CLINICAL MEDICAL EFFECTS OF HEAD AND NECK RESPONSE DURING BIODYNAMIC STRESS EXPERIMENTS

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SUMMARY

Volunteer subjects have undergone impact acceleration experiments at the Naval Aerospace Medical Research Laboratory Detachment (NAMRLD) since 1974. The directions of the applied acceleration are -X (front to back), +Y (right to left), and -X+Y (45° between -X and +Y). The major categories of symptoms were neck pain, headache, restraint related musculoskeletal symptoms, and syncope. A few special cases had findings which required clinical evaluation and followup. The type, extent, duration and severity of the symptoms were related in some cases to the direction, peak acceleration and acceleration duration. There were 1,621 instrumented experiments involving 62 volunteers. Symptoms or signs occurred in 655 (40%) experiments.

INTRODUCTION

The aircrew environment of high performance aircraft includes a complex array of biodynamic stresses. These are: sustained high acceleration, vibration, successive low amplitude impacts often called buffeting, and in emergencies, the succession of impact forces imposed during egress and descent or crashes. A critical physiological limit to aircrew effectiveness and maneuverability is the response of the head and neck which is usually unrestrained and encumbered by a helmet (1-5).

NAMRLD in New Orleans, Louisiana is conducting a continuing program to determine the dynamic response of volunteer subjects to impact acceleration (6-12). A major component of this research requires the measurement of the three dimensional kinematic response of the head to the three dimensional kinematic input at the first thoracic vertebral body (T_1). The head and neck are unrestrained. The independent variables of the experiments are the peak sled acceleration, rate of onset of acceleration, duration of acceleration, direction of acceleration applied to the volunteer and initial positioning of the volunteer's head and neck.

The purpose of these data is to supply a numerical basis for the simulation of the response and for specifications required to construct an anthropomorphic dummy with humanlike dynamic response. In addition the measured kinematic response constitutes a basis to which to relate clinical symptoms, signs and physiological responses of the volunteers. The kinematic response also serves as a basis for comparison of high level animal experiments to the lower level volunteer experiments. The data, derived simulation and dummy specifications are intended for the evaluation of the impact portion of the biodynamic stress environment. The extent to which the data can be applied to other biodynamic stress environments requires experiments beyond the impact experimental design. The clinical signs and symptoms must be carefully observed, recorded, and analyzed as an essential effort in the conduct of volunteer experiments and in evaluating the implications of the measured kinematic response. Physiolcgical limit and injury criteria are developed in part from these observations.

METHODOLOGY

SLED ACCELERATION DEVICE - A Bendix HYGE® pneumatically driven .3048m diameter accelerator is used to accelerate an approximately 1.2m by 3.7m sled of 1,669 kg mass which is rail mounted on 12 Delrin AF® pucks. This type of accelerator has been described previously (13). The acceleration stroke is limited to 1.52m and sled mounted brakes are not used. The effective deceleration drag is about .2G and the sled is allowed to coast to a stop. Total rail length is 213m.

RESTRAINT - During a -X experiment, the volunteer subject is seated in an adjustable chair and fitted with a lap belt, inverted V pelvic restraint and a bilateral shoulder harness restraint. A loosely fitting chest safety strap is also employed. The restraint system is progressively tightened during the pre-run preparation phase in order to minimize unwanted movement by the volunteer during impact (Fig. 1). However, the head and neck are unrestrained.

For +Y experiments, the subject is restrained in a nominally upright position by shoulder straps and a lap belt, inverted V pelvic restraint (Fig. 2). A safety belt, loosely fitted around the chest is also employed. The thrust vector of the sled is directed from the right to the left shoulder and the volunteer is positioned snugly against a lightly padded wooden board used to limit the upper torso motion. The offaxis (-X+Y) experiments were conducted using the same seat and restraint system as in the +Y experiments.

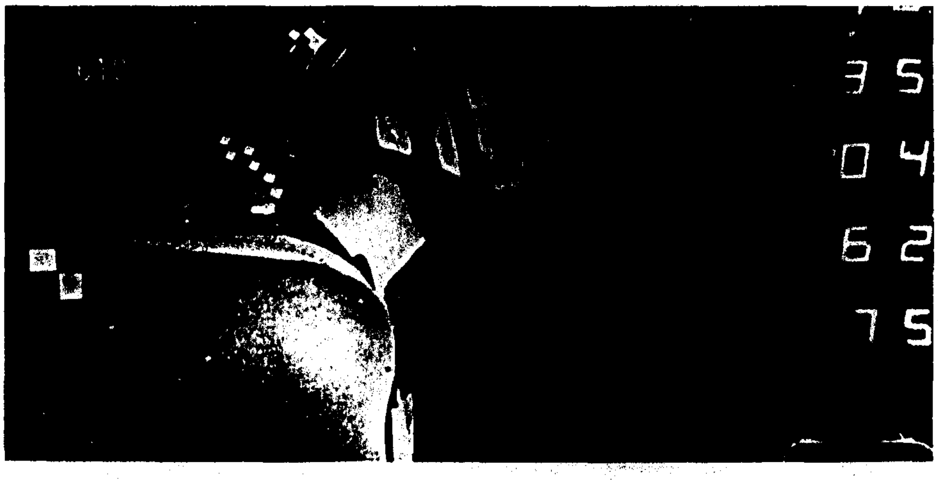


Figure 1. Photograph of a volunteer just prior to a -X impact experiment.

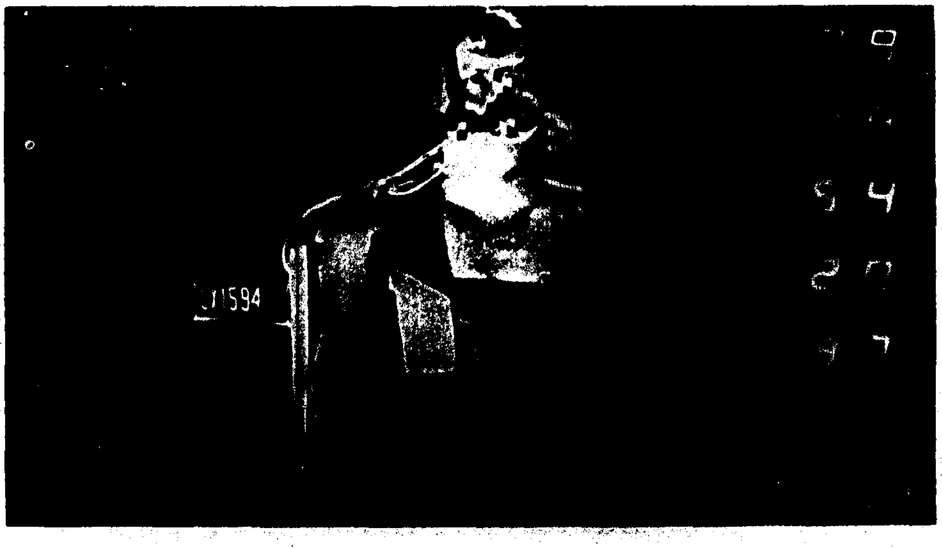


Figure 2. Photograph of a volunteer just prior to a +Y impact experiment.

MECHANICAL RESPONSE MEASUREMENTS - Mechanical response measurements were taken from six piezoresistive accelerometers mounted on a T shaped plate at the mouth and six accelerometers mounted on a T-plate at the spinous process of T_1. The theoretical kinematics of the configuration of the accelerometers on the T-plate and the error propogation associated with this method for determining linear displacement, velocity, acceleration and angular orientation, angular velocity and angular acceleration components of rigid body have been described (14, 15). The cinephotographic system and the two rate gyroscopes used to validate this measurement system have also been described (16).

The standard geometry of the T-plate is illustrated (Fig. 3), showing the position and orientation of the accelerometers.

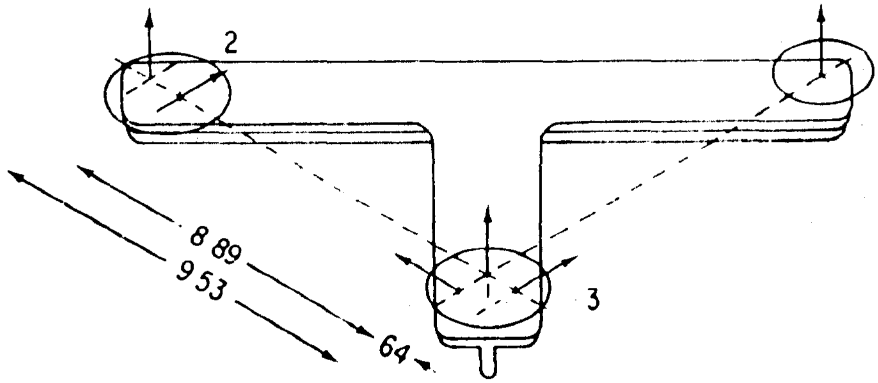


Figure 3. Illustration of T plate instrumentation mount with three accelerometers at one location, two at another, and one at a third (3-2-1 configuration).

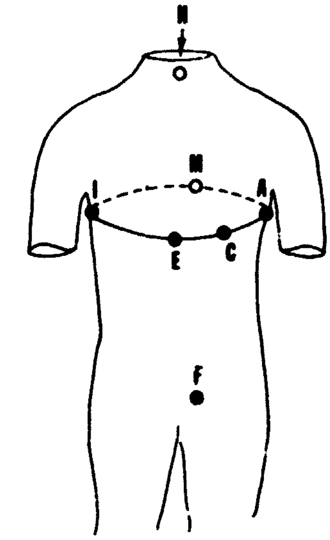
The output of each accelerometer is hardwired to an EAI-pacer 600® hybrid computer, digitized at 2000 samples per second and stored on magnetic disk in real time. The calibration information is available in the computer memory prior to the run and carried with the accelerometer data. Within minutes after each experiment the digital data are scaled and reconverted to analog form. They are plotted on a cathode ray tube for validation by comparison with a scaled light beam oscillographic plot of the data, independently generated at the time of the run. In addition, a two axis rate gyroscope is mounted on the head mount and on the T_1 mount. The data from these gyroscopes are used as an independent measurement of two components of the angular velocity of the head and of the neck.

Cinephotographic coverage of the event is provided by two sled-mounted, pin-registered 16mm, 500 frame per second cameras, Milliken DBM 5D® or DBM 55®, situated orthogonally to each other at approximately one meter from the volunteer. These cameras are equipped with 12.5mm Kinoptic® lenses at f4. Each camera has a 140 degree shutter and is equipped to print ten digits of the time of day at time of shutter opening resolved to 0.1 ms along the frame edge as well as serial IRIG B timing along the opposite edge. One hundred foot rolls of Kodak 2479 RAR® film are used.

Lighting is provided by four sled-mounted General Electric® 4582 lamps mounted in pairs at each of the camera sites. One camera is mounted to the right of the volunteer with lens axis approximately normal to the mid-sagittal plane of the volunteer. The other one is mounted in front of the volunteer. Photographic targets on the T_1 instrumentation mounts as well as the sled-mounted target remain in the field of view of the lateral camera. Targets on the mouth mount instrumentation are in the field of view of both cameras. There is an additional overhead camera for the +Y experiments. The T_1 mount displacement is constrained to the mid-sagittal plane and is measured relative to the sled coordinate system for -X experiments. The three dimensional motion of the T_1 mount is measured for +Y experiments. The mouth mount displacement can be measured in three dimensions relative to the sled. In -X+Y experiments, the photographic coverage is identically placed relative to the volunteer as in the +Y experiments.

THE PHYSIOLOGIC DATA COLLECTION SYSTEM - The physiologic data collection system utilizes an eight-electrode harness, signal conditioning amplifiers, an FM transmitter-receiver telemetry package, an instrumentation quality analog magnetic tape recorder, a pen recorder and oscilloscope monitors. The frequency response of the entire system is flat from 0.1 Hz to 80 Hz, down 4 dB at 0.05 Hz and down 1 dB at 100 Hz. Signal to noise ratio on tape is 55 dB and 80 dB on the pen recorder (17).

Although the electrode placement is in accordance with the system described by Frank, slight modifications have been made to accommodate the anatomic mount placed at T_1. Electrodes at locations I, F, C, A and M have been placed in agreement with Frank. H has been shifted from the posterior neck to the spinous process of the third thoracic vertebra. Lead F has been shifted from the left leg to the left iliac crest (Fig. 4). The electrodes are of the active variety. The skin is prepared by vigorous scrubbing with an acetone moistened sponge. The electrode surface is sparingly coated with a conductive cream and the electrode is placed in the proper anatomic location. The electrode, along with a loop of wire to provide strain relief, is covered with an adhesive backed pad. The individual electrode wire leads are cabled together and attached to the sled mounted amplifier-FM transmitter package by a single connector. The transmitting antenna is sled mounted and located approximately 6 cm from the receiving antenna which runs the entire length of the track. The received FM multiplex signal is conducted by shielded cable to the control room where the electrocardiographic data are appropriately demodulated and stored on analog magnetic tape. The three VCG channels are also written out by a pen recorder and displayed on oscilloscope monitors.



FRANK LEAD ANATOMICAL PLACEMENT

Figure 4

The vectorcardiographic data are collected within an anatomic coordinate system based on the three-axis Cartesian system utilizing the right hand rule. This system is chosen to assure conformity with the other laboratory coordinate systems. The anterior-posterior lead pair is termed X, the left-right pair is termed Y and the superior-inferior pair is termed Z. Anterior, left and superior are positive in polarity. Therefore, the NAMRLD channels X,Y,Z correspond to Frank -Z,X,-Y and approximate the standard leads V2,I,-aVf respectively (Fig. 5).

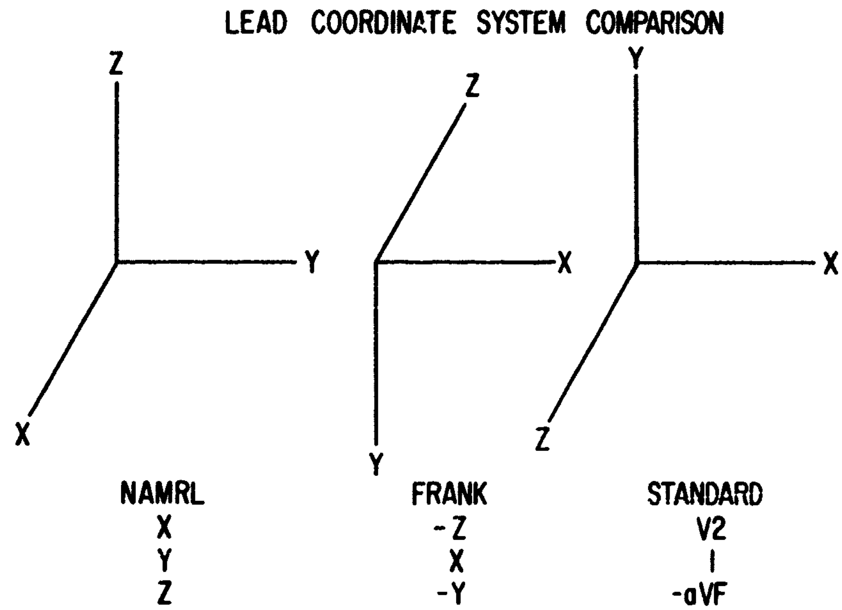


Figure 5

CLINICAL MONITORING PROCEDURES - All volunteer subjects are extensively screened prior to entry into the biodynamics research program at NAMRLD. The procedures, selection criteria, and selection rates for the period 1967 through 1977 have been presented (18). Any volunteer candidate found to have an anomaly, judged to place him at an excess risk of injury from the experiments as compared with a volunteer candidate without the anomaly is disqualified. As a result of this screening effort, a substantial baseline clinical and physiological record is available.

Each volunteer is examined by an attending physician before and after every experiment. The physicians are individually qualified as medical monitors after extensive experience with the research equipment, experimental methods and design. Whenever a volunteer is seated on an operating experimental device, the attending physician is present with the capability to abort the experiment at any time. Each volunteer answers a routine self evaluation at 12 and 24 hours post experiment. In order to standardize and retrieve the clinical record, a highly structured examination record procedure was established. The basic forms, "Medical History Screen" (Fig. 6) and "Physical Examination Screen" (Fig. 7) are presented. This is the entry form to an extensive set of subsidiary forms which are used when a pre-run abnormality or a post-run change is checked on the basic form. There is a subsidiary form for each numbered item on the basic form. All of the data in "check off" form are reduced to punch cards. Observations not amenable to "check off" or which can not be numerically recorded, are written on one of the numbered forms in a narrative and retained. A special case prevails for item 216, "Physiologic data from run." This is an entry point to access the summary judgments from reviews of physiologic data. In all fully instrumented experiments there is a detailed vectorcardiograph clinical summary on a separate form accessed through item 216. Other physiologic measurement systems have been used and are under development.

If the pre and post experiment examinations are normal, the only records are Form 100 "Medical History Screen," Form 200 "Physical Examination Screen," Form 202 "Vital Signs," Form 203 "Visual Acuity and Accommodation," Form 214 "Urinalysis " and Form 216 "Physiological Data from Run." Categories can be added to the basic form, and details changed on the subsidiary forms without changing the logic of the system's ability to retrieve and analyze records prior to the change. The observation from these records constitutes the data base of this report.

1 2 3
NavAerospMedResLabDet Form (1)(0)(0)

Medical History Screen

A. Name ______________________

4 5 6
Initials ( )( )( )

7 8 9 10
B. Subject Number ( )( )( )( )

11
C. Species, sex, race ______________( )

12 13 14 15 16 17
D. Run Number ( )( )( )( )( )( )

18 19 20 21 22
E. Date of Run ( )( )( )( )( )

23 24 25 26
F. Time of Run ( )( )( )( )

27
G. Examination Type (B)

76
Revision (A)

Symptom Category	Col	Pre Run No	Pre Run Yes	Post Run No	Post Run Yes	DP**
101. Headache	28					
102. Visual (blurred, diplopia, field)	29					
103. Vestibular (dizziness, loss of balance)	30					
117. Hearing	31					
104. Morale-Attitude Problems	32					
105. Pain (except headache)	33					
106. GI (nausea, anorexia, bowel) Symptoms	34					
107. Urinary Symptoms (hematuria)	35					
108. Respiratory Symptoms (dyspnea)	36					
109. Cardiac Symptoms (palpitations)	37					
110. Musculoskeletal Symptoms (weakness, stiffness)	38					
111. Others not mentioned in 101-110	39					
*112. Illness since last run	40					
*113. Drug consumption since last run (or past 24 hrs)	41					
* Check Yes if Drug was taken on a routine basis	42					
*114. Alcohol consumption since last run (or past 24 hrs)	43					
115. Narrative	44					
Medically Cleared To Run/Post Experiment Medical Release	45					

Examining Physician's Signature (PRE-RUN) 46 [ ] Physician's Code

Examining Physician's Signature (POST-RUN) 47 [ ] Physician's Code

**DATA PROCESSING (DP) SYMBOLS
(Note: Items 112, 113, 114, use - or + only)

N	N	-
Y	N	$
N	Y	@
Y	Y	+

*Apply to PRE RUN history ONLY

Figure 6

1 2 3
NavAerospMedResLabDet Form (2)(0)(0)

Physical Examination Screen
4 5 6

A. Name ______________________ Initials ( )( )( )

7 8 9 10
B. Subject Number ( )( )( )( )

11
C. Species, sex, race ______________ ( )

12 13 14 15 16 17
D. Run Number ( )( )( )( )( )( )

18 19 20 21 22
E. Date of Run ( )( )( )( )( )

23 24 25 26
F. Time of Run ( )( )( )( )

27
G. Examination Type (B)

76
Revision (B)

Examination *(Normal = N, Abnormal = A, Not Done = ND)
**(Unchanged = U, Significan Change = C, Not Done = ND)

Examination	Col	Pre Run N	Pre Run A	Pre Run ND	Post Run U	Post Run C	Post Run ND	DP
202. Vital Signs	28							
203. Visual Acuity and Accommodation	29							
204. Eye (except fundus)	30							
205. Fundoscopic	31							
Visual Fields (confrontation)	32							
Visual Fields (Goldmann)***	33							
206. Cranial nerves (except II)	34							
207. Skin (bruises, ecchymoses, etc.)	35							
208. Cardiac	36							
209. Pulmonary	37							
210. Abdomen	38							
211. Musculoskeletal (ROM)	39							
212. Reflexes	40							
213. Vestibular (balance)	41							
217. Ears & Hearing	42							
214. Urinalysis	43							
216. Physiologic data from run	44							
218. Clinical Biochemistry	45							

Data Processing Symbols (DP): N N - N Y @
Y N $ Y Y +
(N = No Y = Yes)

	Col	N	Y		N	Y		DP
215. Special Examinations	46							
Medically cleared to run/Post-Run medical release	47							
115. Narrative	48							

____
Examining Physician's Signature (Pre Run) 49 [ ] Physician's Code

____
Examining Physician's Signature (Post Run) 50 [ ] Physician's Code

DATA PROCESSING (DP) SYMBOLS

N	U	-	A	C	+
A	U	$	ND	U	?
N	ND	#	ND	C	!
A	ND	▲	ND	ND	#
N	C	@			

*"Normal" and "Abnormal" refer to the specific subject's baseline examination, and are either normal FOR HIM or abnormal FOR HIM.
** Compared to pre-run examination.
*** Goldman Form 940-2411

Figure 7

EXPERIMENTAL DESIGN

All human impact acceleration experiments with full inertial instrumentation of the head and T_1 are presented for horizontal accelerator runs #156 through #3291. The experiments as summarized (Fig. 8) constitute the experimental design.

The experimental condition is specified by direction of acceleration applied relative to the seated volunteer. The three directions studied are: -X, chest to back; +Y, right to left; and offaxis, designated -X+Y, a direction at 45° between -X and +Y. It is further specified by the peak, duration and rate of onset of acceleration applied to the sled. For each direction three conditions of duration and onset are established which are high onset long duration (HOLD), high onset short duration (HOSD) and low onset long duration (LOLD). Selected initial conditions of head and neck position are studied within the HOLD configuration and the effects on the dynamic response for -X and for +Y direction have been reported (6,12). However, the effect on symptoms and signs is reported for only one special initial condition of neck forward chin down (NFCD) in the -X direction.

There is considerable overlap of rate of onset between the high onset condition and the low onset condition. This is due primarily to the characteristic of the accelerator. The rate of onset is dependent on peak acceleration. Therefore, a low level high rate of onset experiment may have a lower rate of onset than a high level low rate of onset experiment. Also there is considerable variability in rate of onset. On the average, at a given peak sled acceleration the high rate of onset condition is two to six times higher than the low rate of onset condition.

		Sled Parameters					
Direction	Condition	Peak Acceleration Range m/sec^2	Rate of Onset Range m/sec^3	Duration Range ms	End Stroke Velocity Range m/sec	Number of experiments	Totals
-X	HOLD	156 - 19(16G-2G)	30600 - 500	125 - 67.5	18 - 3.4	457	
	HOSD	155 - 47(16G-5G)	28700 - 1350	43 - 22.6	5.4 - 2.4	65	
	LOLD	152 - 56(16G-6G)	4740 - 1030	116 - 91	18 - 8.2	41	
							563
+Y	HOLD	72 - 20(7G-2G)	8700 - 500	150 - 77	6.7 - 3.1	394	
	HOSD	111 - 45(11G-5G)	23600 - 3120	37 - 27	3.5 - 1.9	178	
	LOLD	75 - 20(8G-2G)	1700 - 590	129 - 62	7.5 - 3.2	160	
							732
-X+Y	HOLD	89 - 20(9G-2G)	9470 - 2140	142 - 53	10 - 3.1	122	
	HOSD	129 - 58(13G-6G)	19800 - 6040	35 - 26	3.8 - 2.3	126	
	LOLD	99 - 19(10G-2G)	4400 - 4.3	126 - 69	10 - 3.3	75	
							323
							1,621

Figure 8. Experimental Design. The condition mnemonic is defined in the text.

RESULTS

A total of 1,621 fully instrumented volunteer experiments have been conducted between 31 Jan 1974 and 12 July 1979: 563 -X, 732 +Y, and 323 -X+Y. Symptoms or signs caused by the impact experiment occurred in 655 experiments, with 260 in -X, 287 in +Y and 108 in -X+Y. The incidence rates are 46%, 39%, 33% respectively, and 40% for an overall average.

The most important clinical results are those symptoms and signs with relatively high incidence rates and those which show dependence on the applied acceleration levels. Symptoms of headache are prevalent for -X experiments. The incidence is presented grouped by peak sled acceleration level and experimental condition (Fig. 9). The dose dependency is relatively weak. The short duration experiments have a lower incidence rate. The major finding is a threshold of increased incidences between 10G and 11G, as shown (Fig. 10). The majority of the headaches occur instantaneously with the experiments and are relieved without symptomatic treatment before the close of the workday. The location, intensity, and quality were highly variable. The relationship of the symptom threshold to the threshold for structural damage or injury is poorly defined. In one long duration human experiment on Stapp with sled peak of 40G in which there were a wide variety of serious symptoms (1), permanent structural damage was avoided. Within the HOLD -X condition there are four initial conditions of the head and neck. The neck forward chin down (NFCD) condition was shown to significantly decrease the peak head angular acceleration and linear acceleration (6). There are thirteen 6G and fourteen 10G NFCD experiments. Headache is associated with only one of these experiments, which was at 10G. This suggests that this initial condition, which decreases measured head loading, is also protective against symptoms.

Peak Sled Acceleration	HOLD		HOSD		LOLD	
2	0/3	-				
3	1/40	2%				
4	0/21	-				
5	2/19	10%	0/4	-		
6	2/102	2%	1/19	5%	0/15	-
7	0/19	-	0/4	-		
8	5/27	18%	0/3	-		
9	2/22	9%	0/3	-		
10	10/89	12%	0/16	-	0/2	-
11	11/39	28%			1/4	25%
12	1/12	8%				
13	4/17	23%				
14	7/19	37%				
15	3/22	14%	2/8	25%	3/8	37%
16	2/6	33%	2/8	25%	2/2	100%
	50/457	11%	5/65	8%	6/41	15%

Figure 9. Incidence of -X impact experiments with volunteers reporting headache.

	Headache	No Headache	TOTAL
≤ 10G	23 (5.5%)	395 (94.5%)	418
≥ 11G	38 (26.2%)	107 (83.8%)	145
	61	502	563

Figure 10. Threshold of incidence of headache for -X impact experiments with volunteers.

The other major symptom category is pain, muscular soreness, stiffness, or limitation of range of motion of the neck. The incidence of the neck symptoms for -X experiments is presented (Fig. 11). The incidence shows a threshold response at about 10G and a rise in incidence through the 16G experiments. The symptoms occur promptly with the experiment, tend to persist up to 24 hours, and do not require treatment.

Most of the other -X experiment related symptoms and signs concerned the musculoskeletal system other than the neck. This incidence is much lower. Excluding neck symptoms, complaints of lumbosacral area pain, soreness, stiffness and limitation of motion were the most common, especially as the peak sled accelerations approached 16G. The duration of these symptoms ranged from a few moments to as long as 24 hours. There were, however, no delayed symptoms. In other words, if a symptom occurred, it occurred with impact, and not later. This point is of some significance when compared to the +Y and -X+Y experiments presented below.

Peak Sled Acceleration	HOLD		HOSD		LOLD	
2	0/3	-				
3	0/40	-				
4	0/21	-				
5	1/19	5%	0/4	-		
6	6/102	6%	0/19	-	1/15	7%
7	0/19	-	0/4	-		
8	1/27	4%	0/3	-		
9	1/22	5%	0/9	-		
10	17/89	19%	1/16	6%	2/12	16%
11	11/39	28%				
12	3/12	25%				
13	5/17	29%				
14	9/19	47%			2/4	50%
15	8/22	36%	2/8	25%	2/8	25%
16	3/6	50%	2/8	25%	0/2	-
	63/457	14%	5/65	6%	7/41	17%

Figure 11. Incidence of -X impact experiments with volunteers reporting neck symptoms.

The symptoms and signs reported from the volunteers resulting from +Y impact experiments are predominantly headache and neck related complaints. This is analogous to the findings for -X experiments. The incident rates are presented (Fig. 12 and 13). However, there are major differences. For long duration experiments, the threshold for a significant rate of headache and neck symptoms is about 10G for -X experiments and 6G for +Y experiments. However, it has been previously reported (8, 19) that the acceleration peak at T_1 was much higher for +Y experiments than for -X experiments at any given sled acceleration. This is due to the rigid right side restraint for the +Y experiments which caused higher acceleration at T_1 than in -X experiments at the same sled acceleration. The lower sled acceleration threshold for significant symptom rate in the +Y experiments is explained by this difference in restraint. Therefore, there appears to be little difference in the threshold of T_1 acceleration response for symptoms between lateral and frontal impact.

Peak Sled Acceleration	HOLD		HOSD		LOLD	
2	0/39	-			0/11	-
3	2/82	2%			1/26	4%
4	4/42	10%			1/26	4%
5	14/118	12%	0/22	-	6/45	13%
6	12/54	22%	1/23	4%	6/24	25%
7	15/59	25%	1/24	4%	9/24	37%
8			2/22	9%	3/4	75%
9			7/27	26%		
10			4/37	11%		
11			8/23	35%		
	47/394	12%	23/178	13%	26/160	16%

Figure 12. Incidence of +Y impact experiments with volunteers reporting neck symptoms.

Peak Sled Acceleration	HOLD		HOSD		LOLD	
2	0/39	-			0/11	-
3	0/82	-			1/26	4%
4	2/42	5%			2/26	8%
5	3/118	3%	0/22	0	6/45	13%
6	6/54	11%	1/23	4%	3/24	12%
7	15/59	25%	3/24	12%	4/24	17%
8			0/22	0	0/4	0
9			3/27	11%		
10			3/37	11%		
11			7/23	30%		
	26/394	7%	17/178	10%	16/160	10%

Figure 13. Incidence of +Y impact experiments with volunteers reporting headaches.

The quality and localization of the headache and neck symptoms is vector dependent. Delayed onset headaches are usually persistent. Similarly, the neck symptoms are often delayed in onset and almost always on the left side of the neck in the area of maximum extension of the neck. Also, "neck popping" occurs frequently, and is noted at impact and without sequelae post run. This symptom has never been reported for -X experiments.

There was one volunteer who was dropped from the program because of neck symptoms as a result of a +Y experiment. Volunteer H067 sustained electric type sensation, tingling and then numbness of the right arm and shoulder. The peak sled acceleration level was 6.2G. This volunteer was very experienced and had prior exposure up to 7.5G in this direction. The most dramatic symptom lasted only a second or two and was gradually replaced by minor discomfort in the right neck area lasting 9 days. Detailed examinations by a neurosurgeon were completely normal except that volunteer carried his head slightly tilted toward his right shoulder. This postural variation predated his volunteer service. It was finally concluded that a postural facet syndrome existed which became manifest indicating in retrospect that he should not have been used as a volunteer. This was confirmed by orthopedic followup several months later.

Three volunteers had unique signs and symptoms in the +Y vector related to body physique. Volunteer H097 because of size would routinely bump his right thigh and ankle upon impact against the rigid lateral restraint board. Volunteer H078 because of bony prominence of spinous processes and elbow would have soreness of these areas on impact, and also soreness under the T_1 mount. Volunteer H096 had frequent discomfort in the thoracic spine area from T_4 to T_{11}. This could be related to mild thoracic scoliosis in this area.

Relatively infrequent complaints that appear to be related to the restraint system are (1) soreness of left shoulder from the shoulder restraint, (2) sore right neck from T_1 strap, (3) soreness in right thigh, shoulder, arm, and elbow from the lateral board restraints, (4) abrasion of left arm from metal buckles of the chest strap system, and (5) soreness on impact at site of ECG electrode placement.

The incidence of -X+Y experiments in which the volunteers experienced headache or neck symptoms is presented (Fig. 14 and 15). The incidences are comparable to that for +Y experiments. This implies that the T_1 and head loading was at comparable levels for this direction. However the kinematic data analysis of the -X+Y experiments is incomplete. It should be noted that -X+Y experiments were executed at higher levels than +Y experiments. In the +Y experiments the levels were limited in order to avoid experiments in which head strikes against the right shoulder rigid restraint might have occurred.

Peak Sled Acceleration	HOLD		HOSD		LOLD	
2	0/20	-			0/10	
3	1/21	5%			0/11	
4	1/16	6%			0/9	
5	1/20	5%			1/10	10%
6	5/16	31%	0/16	-	4/14	29%
7	3/17	18%	1/16	8%	3/7	43%
8	1/8	12%	0/17	-	2/6	33%
9	2/4	50%	0/15	-	3/5	60%
10			1/15	57%	1/3	33%
11			8/25	32%		
12			4/12	33%		
13			3/10	30%		
	14/122	11%	17/126	13%	14/75	19%

Figure 14. Incidence of -X+Y impact experiments with volunteers reporting neck symptoms.

Peak Sled Acceleration	HOLD		HOSD		LOLD	
2	0/20	-			0/10	-
3	0/21	-			0/11	-
4	1/16	6%			0/9	-
5	0/20	-			1/10	10%
6	1/16	6%	0/16	-	0/14	-
7	0/17	-	1/16	6%	2/7	29%
8	0/8	-	0/17	-	1/6	17%
9	0/4	-	2/15	13%	1/5	20%
10			3/15	20%	0/3	-
11			3/25	12%		
12			4/12	33%		
13			8/10	80%		
	2/122	2%	21/126	17%	5/75	7%

Figure 15. Incidence of -X+Y impact experiments with volunteers reporting headache.

More than half of the neck symptoms reported for -X+Y experiments were delayed in onset to a greater degree than +Y or -X experiments. A minimum of 12 to 24 hours is required to evaluate any delayed onset symptoms. One volunteer sustained a strain of left posterior cervical soft tissue and interarticular ligaments with traction or compression of the posterior nerve roots C_5 through C_7. This resulted from a -X+Y experiment at 7G in the LOLD condition. Symptoms did not resolve completely until 10 days post experiment. X-rays and bone scan were normal. During a 3-month followup there was no recurrence of symptoms. No underlying condition was implicated in this case.

Alterations of the electrocardiogram also occurred. These findings are primarily bradycardia, suppression of the sinoatrial node, intraventricular conduction abnormalities, and minor T wave changes. All the electrocardiographic abnormalities returned to baseline within 3 minutes post run. A single case of evolved EKG changes to suggest myocardial contusion has been reported in detail (17).

Incidence of experiments with VCG changes for -X was 72/207 (35%), for +Y 115/730 (16%), and for -X+Y 39/307 (13%). The detailed analysis of the significance of these findings is under investigation. Case reports from impact experiments have been previously reported (17, 20).

Skin abrasions also occurred rather infrequently, and these were always due to the restraint system. None of the skin lesions persisted for more than a few days.

Another problem which is directly related to the restraint system was syncope. These episodes usually occur with a newly qualified volunteer on his first or second fully instrumented run. A 7.5cm wide circumferential chest strap is used to aid in maintaining the T_1 neck mount in place. This strap is tightly applied and definitely limits chest expansion, thus interfering with respiration. The lap belt, inverted V restraint, when tightened, restricts venous return from the legs. The shoulder straps restrict venous return from the arms. In combination, these straps effectively impede both circulating blood volume and pulmonary gas exchange, predisposing the volunteer to syncope under the additional stress of his first experiment. The newly qualified subject, after one of these unpleasant episodes, learns how to breathe diaphragmatically, and in each case, is able to adapt to the stress, so that only four volunteers had more than one such syncopal episode. There were 18 pre-run syncopal episodes. The attending medical officer aborted the experiment in each case. No volunteer was ever impacted while syncopal. One of these cases resulted in 5 seconds of asystole (Fig. 16). No injury resulted, since the subject was removed from the restraint and instrumentation devices within 60 to 90 seconds. However, he was disqualified because of lack of nodal escape mechanism.

Eleven instances of syncope occurred after impact. In seven of these, the sled peak acceleration was over 10G, with three at 16G. These episodes occurred in well seasoned volunteers, and thus must be due to these highly stressful experiments. As with the pre-run syncope, each subject was speedily removed from the sled, recovery was rapid, and no injury resulted. Virtually all the syncopal attacks to date occurred in the -X configuration with only three in the +Y and none in the -X+Y series. Of the three syncopal attacks in the +Y experimental series, two occurred pre impact and one occurred one minute post run. No problems were noted after the volunteer was taken out of the restraint system and the mounts removed.

DISCUSSION AND CONCLUSIONS

The clinical findings have been presented and analyzed by vector direction, sled acceleration peak and duration. Those findings which are run related and due to inertial loading of the head and neck are primarily headache and neck strain. Most headaches occured promptly and some were of delayed onset. Two cases of neck strain were sufficiently severe to warrant removal of the volunteers from further experimentation. The quality of the neck symptoms is markedly different depending on vector direction. This conclusion must be qualified with the understanding that the head and neck inertial loading is much more severe in +Y experiments than in -X experiments for a given sled acceleration peak and duration. This is due to the sideboard restraint used in the +Y experiments that increased the T_1 and head response for a given sled acceleration above that seen for -X experiments (8, 19). The transition levels from transient symptoms to injury to permanent damage in humans are unknown. However, experiments with baboons (Papio anubis) (21) and rhesus monkeys (Macaca mulatta) (22, 23) indicate structural failure of the atlanto-occipital articulation for -X experiments between 100G and 120G on the sled. An experimentally based estimate of injury limits for man is under study by means of measuring transient neurophysiolgical response of the Macaca at the lower sled acceleration levels (24, 25).

Important cardiac changes have been previously discussed (17). They are attributed to inertial loading of the heart and/or inertial loading the vascular and neurological structures of the head and neck. This results in extensive vagal response previously demonstrated by Taylor (20). These changes also are related to the post experimental syncopal episodes.

Other findings are not systematically related to the inertial response. They exhibited wide variation and type or are unique to the physique of individual volunteers, particularly as related to fit in the restraint system.

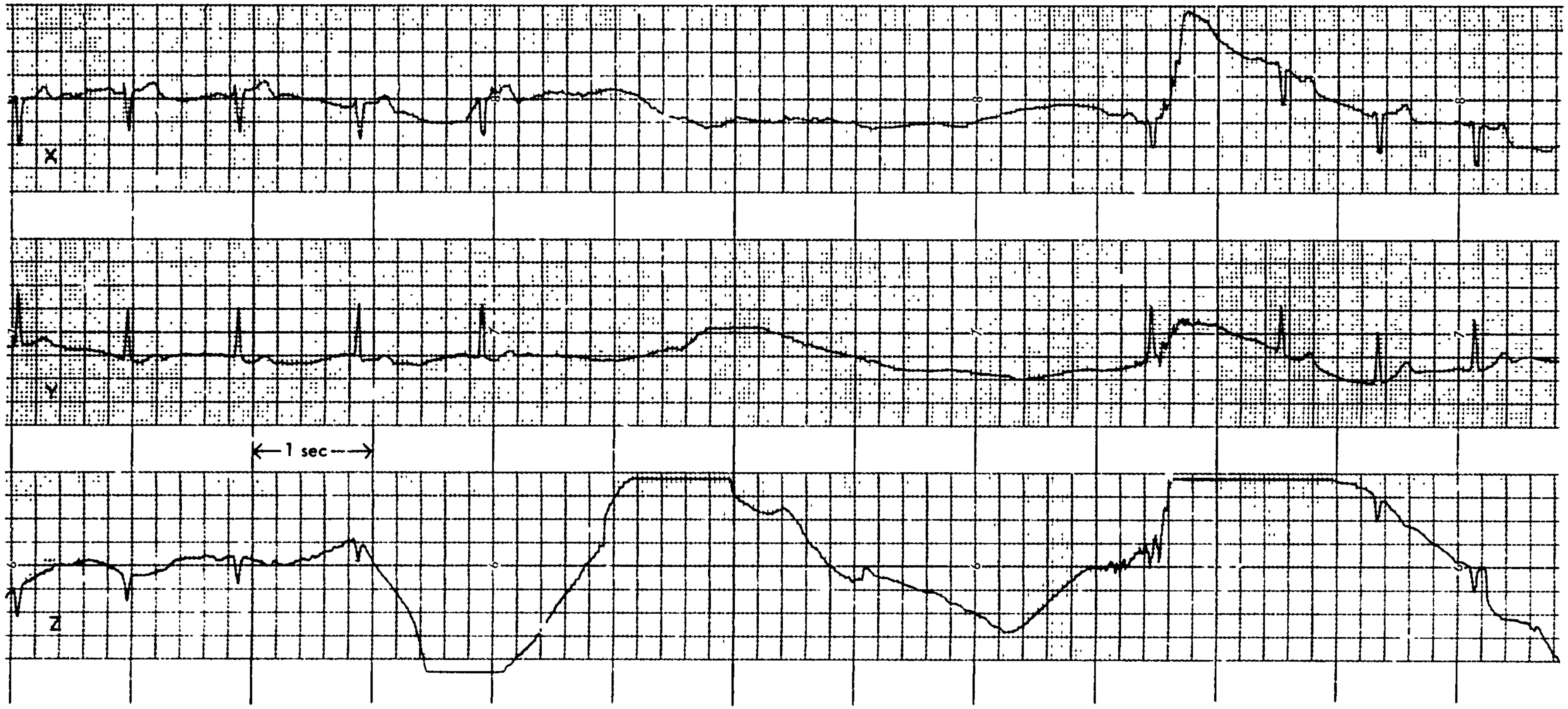


Figure 16. Pre-experiment episode of asystole and syncope. Experiment #LX1063 planned for -X, 10G, LOLD halted 8 seconds prior to asystole due to clinical condition of volunteer.

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Opinions or conclusions contained in this report are those of the authors and do not necessarily reflect the views or the endorsement of the Navy Department.

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OPERATIONAL ASPECTS OF GUIDANCE AND CONTROL ADVANCES VS PILOT WORKLOAD FOR LOW ALTITUDE, HIGH SPEED FLIGHT

by

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Guidance and control and pilot operation have a number of characteristics that are common in that both behave according to basic control and information theory and, in many cases, are equally describable by similar analytical methods. It was on the basis of this similarity that the terminology cybernetics was initially created. The first application of guidance and control to aircraft was Dr. Elmer Sperry's automatic stabilizer, later called autopilot, for which he received a 50,000 French franc prize in 1914 for the most stable and safest aircraft. His main purpose in developing this system was to provide a mechanism to relieve the pilot from the detailed task of continually stabilizing the vehicle and thereby making it a useful machine. Figure 1 is a functional diagram of this system which illustrates some of the basic feedback principles involved. To provide some background for later discussions, the following will discuss some of the characteristics of the human operator and their similarity to guidance and control functions[1]. The operator's characteristics as a controller depend on four kinds of variables: control task variables, which include the system inputs and all the system elements external to the operator; environmental variables such as ambient illumination, temperature, vibration, etc.; operator-centered variables such as training, fatigue, motivation; and procedural variables such as instructions, practice, order of presentation relating to a given task. When these variables are essentially time stationary or invariant over an interval of interest, the operator vehicle system can be modeled as a quasi-linear system much the same as standard servo loops.

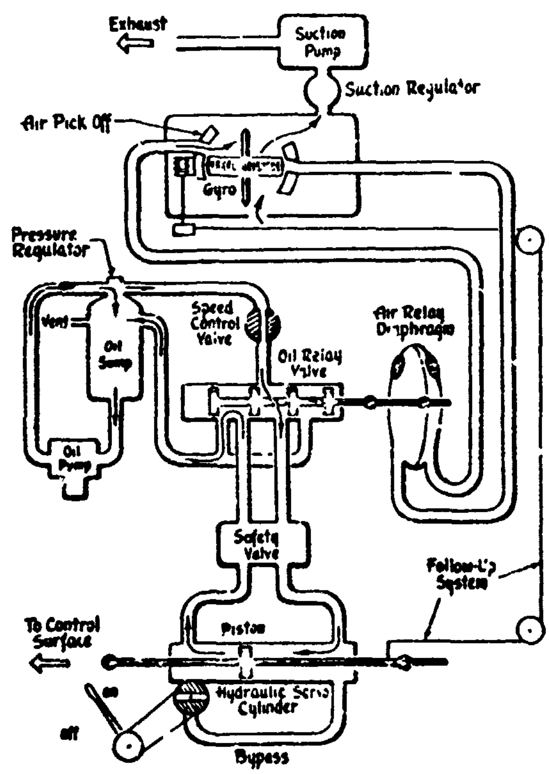
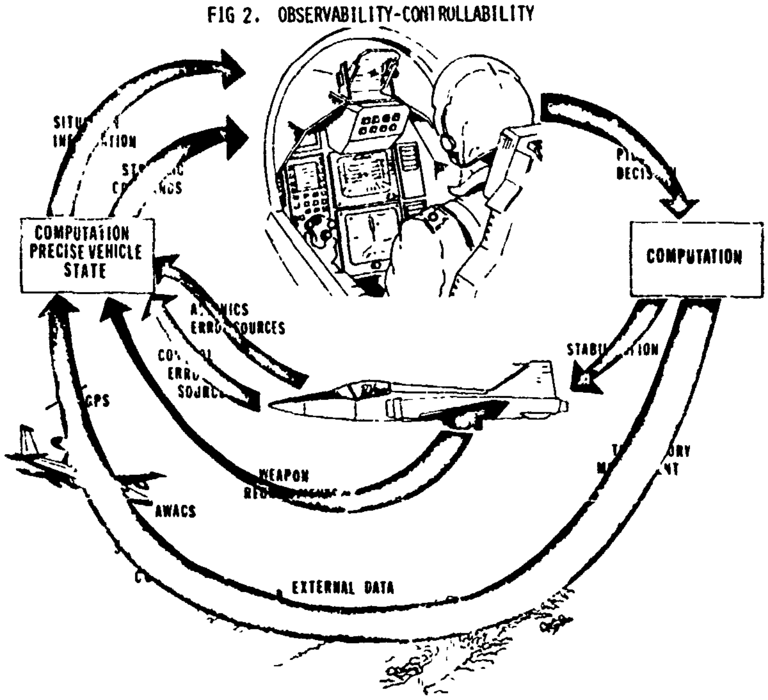


Figure 1- Early Sperry Autopilot

Figure 2 tends to illustrate some of these relationships showing that the major part of the human operator problem is really one of observability and controllability, and the fact that one of his major tasks is the integration of all the information available and attempting to determine the strategy or control aspects that best satisfies the objective of the mission task to be achieved.

FIG 2. OBSERVABILITY-CONTROLLABILITY



The fundamental aspects of manual vehicular control theory can be briefly summarized as follows:

a. To accomplish guidance and control functions, such as flying a desired track in the presence of disturbances, maintaining position control as in formation, terrain following or refueling, and flying intercepts or approaches, the human operator structures a variety of closed loops about the vehicle to achieve the control actions and functions desired in terms of actual vehicle motions and flight path.

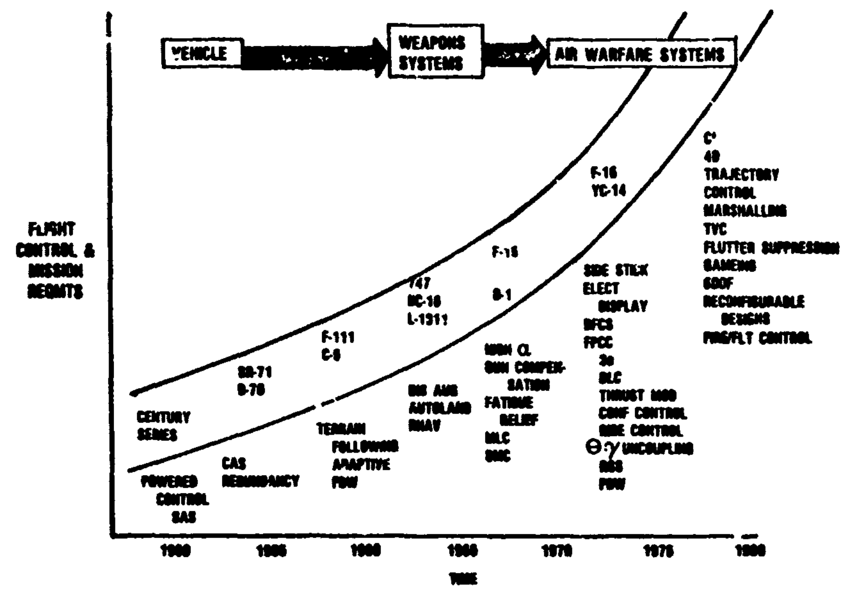
b. To be satisfactory, these closed loop systems, which include both active and passive elements, must share certain of the dynamic characteristics of a good closed-loop control and stabilization system. As the adaptive element to accomplish this end, the pilot must make up for any dynamic deficiency of the system by appropriate adjustment of its dynamic properties. This is the terminology that was referenced as integration in the form of Figure 2.

c. The cost of this adjustment is fundamentally workload and can consist of stress, which includes vibration, hazards, and environment, concentration of operator faculties on the mission task dynamics, and the capability to cope with the unexpected. This, then, illustrates why there is a close relationship between guidance and control and pilot workload in that the guidance and control systems can be implemented and designed to reduce many of the normal pilot operator functions as well as defining the true information or states required for the pilot to execute his mission.

To illustrate some of the trends and history of guidance and control over the past few decades, the next slide (Figure 3) illustrates briefly what these guidance and control technology trends are. It summarizes some of the transitions that have occurred over the past two and a half decades, beginning with the 1950s[2]. But most significantly, it illustrates two basic trends: the first is the increase in guidance and control functions and requirements; the second is the progression from vehicle to weapon systems into what we now call air warfare systems. During the early 1950s, the trend was predominately vehicle oriented in terms of stability augmentation systems to improve the response in control characteristics. This was followed by closed-loop terrain following systems to improve adverse weather, low altitude performance in safety aspects of the system. Adaptive system concepts became operational in the F-111. These concepts, which have been discussed extensively in other publications, contributed substantially to the current modern control theory and technology. As a sideline, a seldom recognized fact is that the Kalman filtering theory was a direct outgrowth of the theoretical work undertaken to describe, analyze, and design adaptive systems.

Emergence of fly-by-wire technology in various forms became evident during the early 1960s with fly-by-wire spoiler controls on the F-111 and the electronic flight control on the French MIRAGE. Increased use of inertial sensors and navigation systems to augment vehicle of flight path control for reducing landing minimums, and improve interaction with area navigation and advanced air traffic control concepts during the early 1960s, represents initial steps in the functional integration for increased performance and workload reduction. During the mid-1960s, the benefits of feedback control could offer in alleviating structural fatigue problems and turbulence sensitivity were recognized. This work culminated in the application of maneuver load control and structure load

FIGURE 3: **CONTROL TECHNOLOGY TRENDS**



control to alleviate turbulence induced fatigue problems, and improve crew ride quality in the B-1 and other systems. Progressing into the early 1970s, the MRCA, the Swedish Viegin, French Concorde, the F-16, and YC-14 designs witnessed incorporation of side-stick controllers, electronic displays, increased emphasis on digital techniques, control and propulsion system dynamic interaction, direct lift control, ride control, and relaxed static stability, all of which were made possible through implementation of emerging technology.

In looking toward the future of air warfare systems, the impact that command and control and communications will have on the vehicle guidance and control in terms of tactical control is significant. This need generates another guidance and control dynamics loop which dictates substantial dynamic and functional interaction to provide the desired operational capability. The time-space positioning capability permitted through accurate position fixing, employing advanced navigation systems, and the onboard vehicle trajectory control permits the implementation of the command and control function to marshal forces for tactical deployment and, also, offers a means for redirect capabilities.

The six-degree-of-freedom control projected through active control technology permits design freedom and tactical capabilities unavailable heretofore other than in specialized rotary wing configurations. These capabilities have stimulated application of modern control theories involving strategies, differential gaming, to determine means that can provide optimum trajectories and tactical options to increase weapon delivery accuracy and minimize pilot workload.

With this brief overview in projection, let's examine advances in guidance and control to determine how they can be employed to reduce pilot workload, particularly in the low altitude, high-speed regime. A considerable amount of work has been performed on the application of stabilization systems to reduce pilot workload. However, the majority of these systems have not reduced the pilot workload to any large degree because, in most cases, they introduced unconventional methods of control which, in themselves, created a learning problem[3]. The learning of these new control techniques aggrevated, in many cases, the workload problem. Also, many of these developments concentrated primarily on the control aspects ignoring the information display aspects which provides the necessary information for the pilot to act as a closed-loop controller.

The problem associated with combining guidance and control systems or automatic systems with pilot operation is the mechanism of pilot interaction. This is somewhat analogous to the cruise control on an automobile which works perfectly for cruising on a highway; its use in traffic, however, involves a tremendous amount of switching and other unconventional manipulation. In terms of control, the first attempt to solve some of these problems was control wheel steering wherein a switching or sensor mechanism on the wheel or stick was employed to sense applied force by the pilot in a normal manner, deactivating some of the stabilization modes of the system and, thus, restore normal aircraft maneuvering response. This proved successful to a degree but the fundamental control laws involved were for stabilization, and the limited authority of the system made it extremely restrictive and added to the pilot workload rather than easing it. A more successful approach was the command augmentation system design. This is illustrated in Figure 4 and shows the requirements and characteristics involved, the typical representation of the system and, finally, the basic issues involved. The command

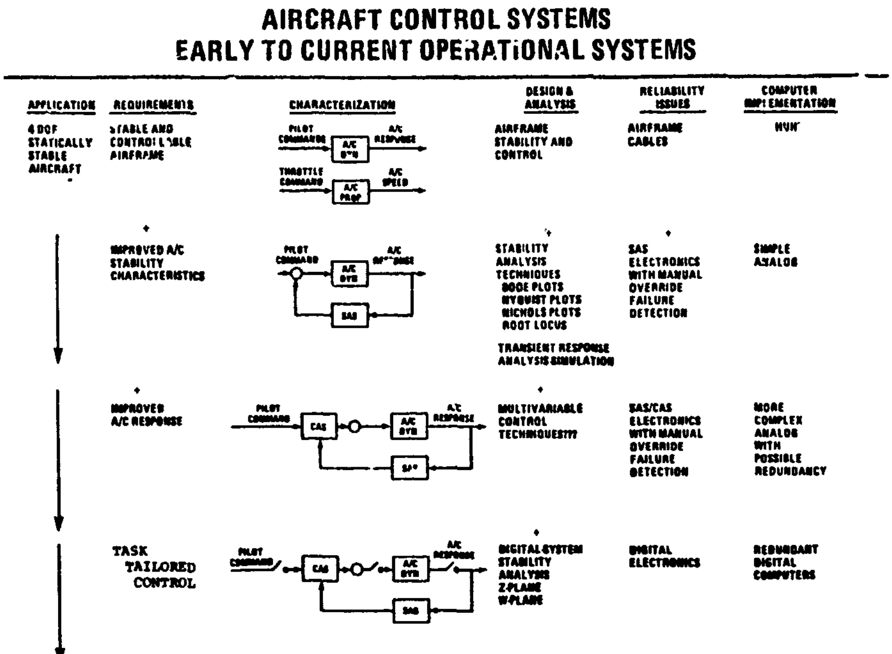
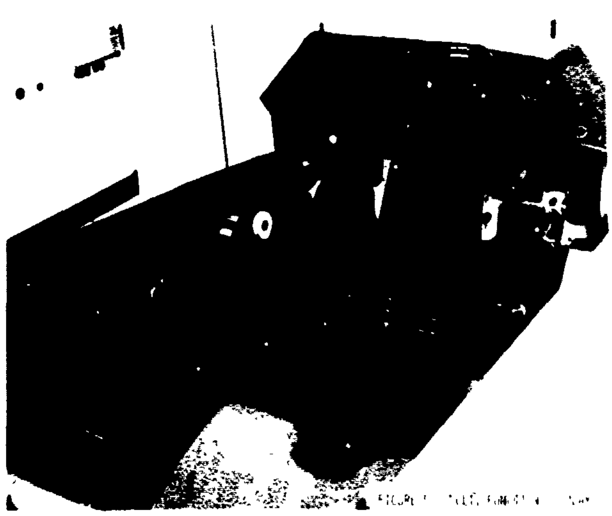


FIGURE 4.

augmentation system provided a means for enhancing the stabilization properties of the vehicle without deteriorating the maneuvering performance while at the same time provided an input and control law capability that made the vehicle behave in a manner that was very desirable from the handling qualities standpoint. This was successful for the traditional up-and-away and some precision tasks such as approach and landing; however, for certain weapon delivery or mission functions, the general control laws were proven inadequate. Further control analysis and flight research experience indicated that an approach termed task-oriented control laws wherein the control characteristics of the vehicle are deliberately configured to provide precision control and performance for that particular mission would be a solution. These have eliminated many of the problems of integrating the pilot with the control system and are proving very successful, and indicate that the vehicle control aspect of the problem is solvable employing guidance and control design technology. As stated earlier, the other aspect of pilot workload is information integration and how the pilot interacts with the new mission functions that are becoming information dominated as the complexity of the mission increases. This has resulted in a design change toward electronic display techniques that can be made multi functional and are more amenable to alphanumerics and graphic symbology[4]. One such configuration is shown in Figure 5 and illustrates a multi-function array using electronic cathode ray tubes. This approach permits the selection and presentation of necessary information to perform the function while at the same time subduing some of the related information thereby reducing clutter. However, one of the basic problems with this approach is, how can the pilot interact with the display in order to make it natural and harmonious?.



Research activity in this area of attempting to better achieve the more harmonious, or blended system design, is typified in Figure 6 which illustrates in general form both the nature and characteristics of the problem. This is intended to show that, characteristically, we have worked in the vertical plane which consists of the vehicle, the pilot and advances in basic control elements without really considering the horizontal aspects or mission function. This approach stresses the need to look across in terms of sensor, the vehicle, and mission functions, or kill mechanism, thereby illustrating the dominance of information and its role in the mission and system design. This now addresses an integration function and the need to provide a capability to integrate the pilot, the vehicle, and the mission into a harmonious set. The results of this research work has lead to an approach called flight management systems wherein a deliberate attempt is being made to define approaches and implementation that will make the system more easily controlled through task-oriented control laws and, at the same time, provide to the crew the necessary information which is harmonious with control laws to achieve this mission function. Some of these are displayed on Figures 7 and 8, which illustrate a basic crew configuration used for discriminatory purposes. As you can see in the chart, through the use of color the identification time is drastically reduced. A specific experiment in this area indicated about 50 percent reduction in identification time.

BLENDED SYSTEM DESIGN
(INTEGRATED CONTROL DESIGN TECHNOLOGY)

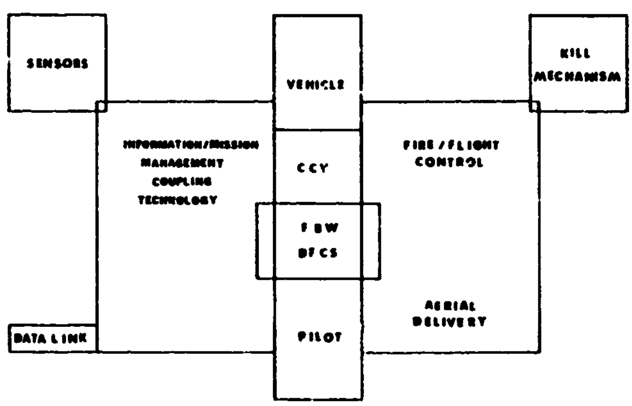


FIGURE 6.

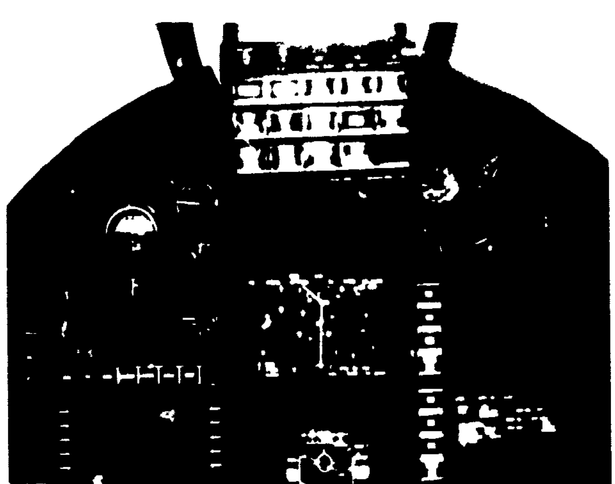


FIGURE 7. EXPERIMENTAL COCKPIT

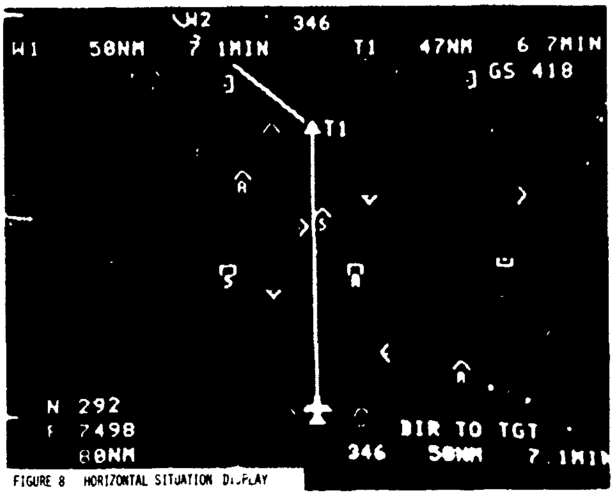
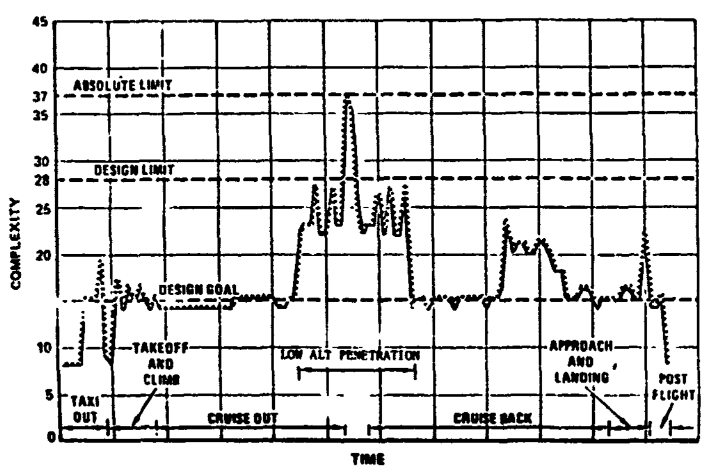


FIGURE 8 HORIZONTAL SITUATION DISPLAY

The next section now will stress specific problems associated with low altitude, high speed environment. The principle factors involved in low altitude, high speed operation are:[5] The physical environment, turbulence, vibration, and fatigue; the second is vehicle integrity and responsive characteristics. From the vehicle standpoint, the pilot is always concerned about vehicle stability, safety in terms of controllability/control performance, degradation, and visual environment; if it's night and adverse weather, the reliability of sensors that provide synthetic vision needs such as radar or low light TV. And finally, their concern over the overall hazards and vulnerability aspects while in this low altitude environment when vehicle vertical and horizontal positioning becomes critical. The next chart, Figure 9, illustrates an analysis that was performed which tends to show how stress levels increase as proximity to the ground is approached or when a target is approached in a highly concentrated environment[6]. In terms of the turbulence or vibration environment, the following chart, Figure 10, shows a tolerable and intolerable region in terms of exposure time in minutes and vertical acceleration which illustrates for short periods of time a relatively high level of vertical acceleration can be tolerated but as exposure time increases the tolerance region drastically reduces. Similarily, one of the problems with this region of flight is that the higher rms accelerations increase the difficulty to read instruments or to provide precise tracking because the pilot is unable to discern whether the vehicle disturbance is due to turbulence or due to failures in the system[7]. Similarily, it is interesting to note that frequently the major cause of the acceleration at the pilot station is body bending modes for structural elasticity. It is also interesting to note that the frequencies that occur with this structural mode also tend to coincide with internal organ frequencies of the human body, thus making it more fatiguing and less tolerable.

FIGURE 9. WORKLOAD ANALYSIS



From the guidance and control standpoint, we have taken approaches whereby through structural mode compensation and ride control characteristics such as employed on the B-1 and also shown on the next figure, #11, a B-52, a means whereby accelerations at the pilot station can be reduced and thereby improve the environment and operation at low altitudes[8]. The second area of concern is that of vehicle precision control and accurate positioning at low altitudes. Several approaches have been investigated recently relative to this; one that appears to be of extreme interest is the activity referred to

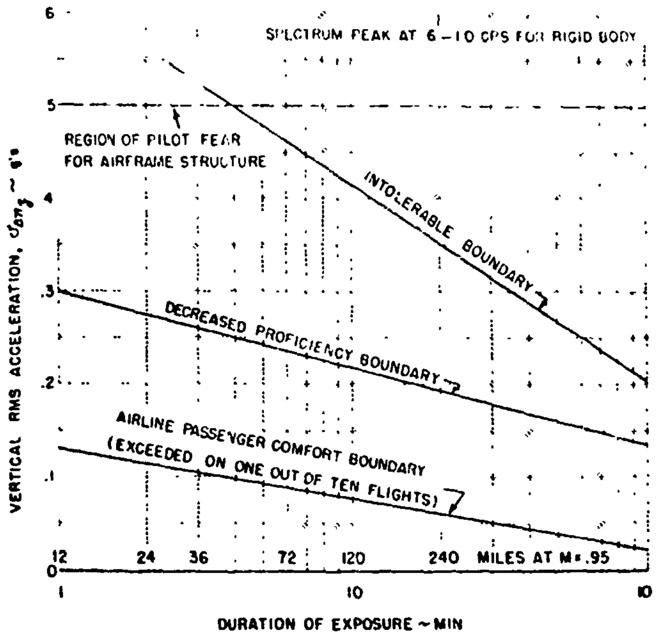


FIGURE 10. TIME-INTENSITY VIBRATION BOUNDARIES

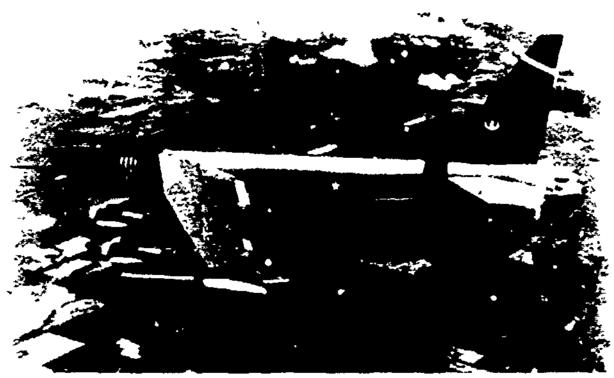


FIG 11. B-52 CCV ([illegible])

as active control technology or CCV technology. [illegible] application of CCV technology whereby we could [illegible] improve the precision of control at these extremely low altitude [illegible] similar program was performed on the CCV YF-16 which als[illegible] can be provided through guidance and control, Figure #13.

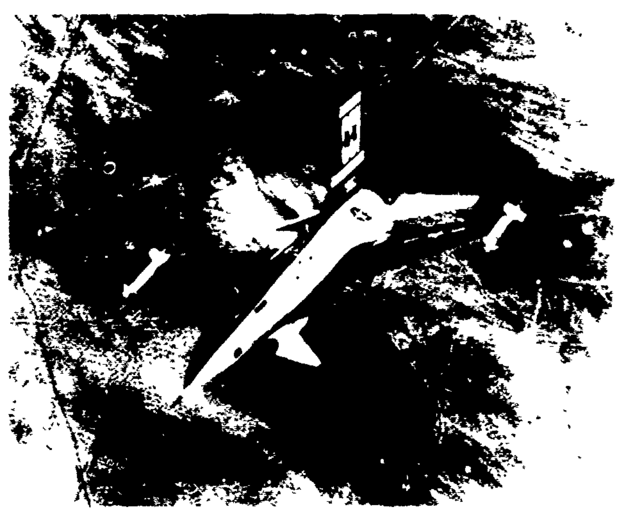


FIG. 1[illegible] F-16 CCV (CONTROLLED CONFIG[illegible])

CCV FLIGHT TEST SUMMARY

AIR-TO-AIR TASKS	MANEUVER ENHANCEMENT/ GUST ALLEVIATION	DIRECT FORCE A_N	DIRECT FORCE A_Y	FUSELAGE POINTING α_1	FUSELAGE POINTING β_1	TRANSLATION α_2	TRANSLATION β_2
TRACKING	G	G	G	G	G	Y	Y
DEFENSIVE MANEUVERING	G	G	G	N/A	N/A	Y	Y
FORMATION/STATION KEEPING	G	Y	Y	N/A	N/A	Y	Y
AIR-TO-GROUND TASKS							
STRAFING	G	Y	G	G	G	Y	G
DIVE BOMBING	G	Y	G	N/A	Y	Y	G
APPROACH/LANDING	G	Y	Y	Y	Y	G	G

GREEN - POTENTIAL IMPROVEMENT

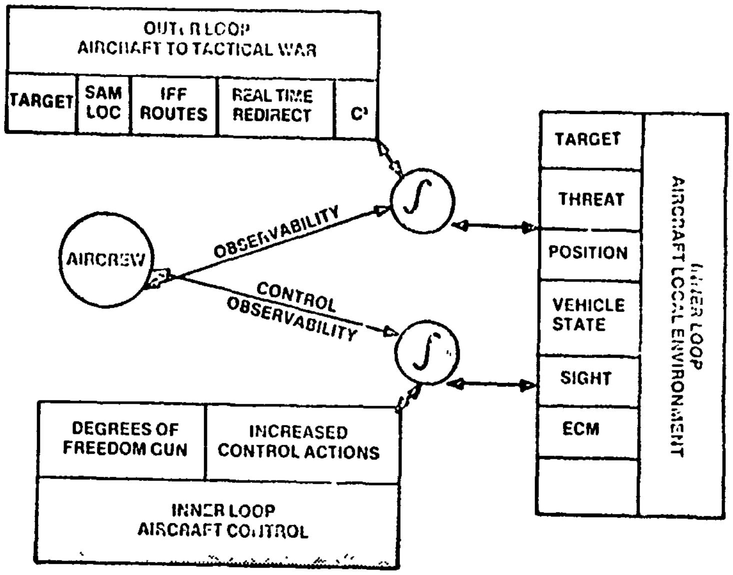
YELLOW - INCONCLUSIVE/CONFLICTING ASSESSMENT

FIGURE 13.

The next area of concern is that of synthesizing the visual environment such that the pilot can continually observe his situation and the characteristics of the terrain beneath him without having to concentrate on the details of the activity. An approach to this has been the flight management system which has not been flown to any degree, but similar approaches have been flown as I will show later. The key to this is the application of color to synthesizing the major features of the terrain and overlaying these on a horizontal situation display, such as shown on Figure 14, wherein the pilot can continually observe his vertical and horizontal track over the terrain beneath him and, also, observe the variations in terrain during flight. In addition, threats or other hazards can also be illustrated on this map and groups can be projected such that the pilot can fly manually or the system can automatically generate a trajectory to circumvent these hazards. In general, although this has been a very brief synopsis of guidance and control activity that can reduce workload, I think you can now observe that knowledge and fundamental technologies are available to address this problem. The next step is developing some of the analytical techniques capitalizing on those we have already performed as shown on the following chart, Figure 15, to address from a more total standpoint the area of pilot workload using modern control theory whereby the controllability/observability principles can be applied in a manner such that sensitivities to various states and identification of states that must be presented that can be readily applied. This next chart, Figure 16, illustrates how we perceive the futuristic cockpit to look and provide what we feel is a one-man, night all-weather low visibility at low altitude.

FIGURE 14. TERRAIN FEATURES (MAP DISPLAY)

FIGURE 15. **CONTROLLABILITY/OBSERVABILITY**



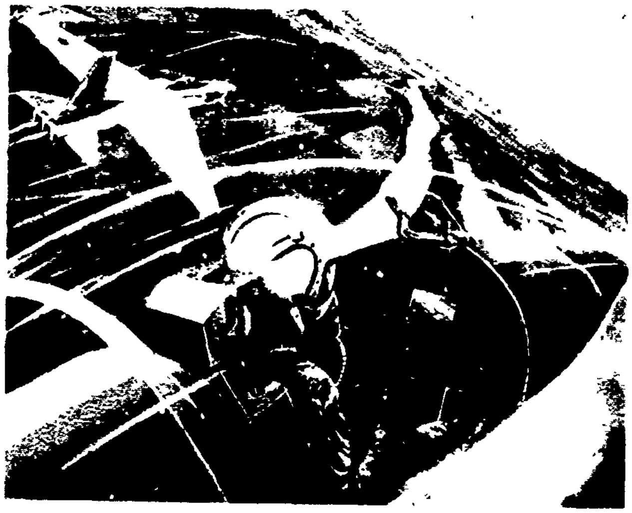


FIGURE 16. FUTURISTIC COCKPIT

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TV OPERATOR PERFORMANCE IN REAL TIME AIR-TO-GROUND RECONNAISSANCE MISSIONS UNDER TASK-LOADING CONDITIONS

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SUMMARY

The detection performance of a black-and-white-TV operator in real time reconnaissance missions is determined by the parameters of the RPV-system, the scene, and the task. A series of 6 experiments was performed with 19 untrained subjects who had to find military vehicles in static ground scenes displayed on a TV screen. The scenes were presented only shortly, for 1 to 10 secs. This corresponds to a speed of about 50 to 500 km/h at a nonoverlapping frame rate. The subjects pointed to located targets with a light-pen. Analysis of variance indicate that the detection rate is influenced by:

- scene parameters which constitute the conspicuity of a target in a natural scene, such as global context, contrast and local context
- short presentation times of less than 3 secs
- system parameters such as resolution and image segmentation
- number of targets. Detection rate decreases if the task is to mark all targets and detection rate increases if the task is only to indicate those scenes which contain at least one target.

The false alarm rate decreases with the number of sessions the subjects took part in and was finally at low level. Taking the confidence level expressed into account proved to increase the detection-false alarm ratio remarkably. Search times were nearly equal to presentation times from 1 to 5 secs only. The search times for the 50 % detection rate decreased from 4 secs in the first experiment to 2 secs in the last one. Questionnaires were filled in.

1. INTRODUCTION

The performance of a TV operator is of growing interest because of military demands for air-to-ground reconnaissance by remotely piloted vehicles (RPV) under real time conditions. Investigations of real time reconnaissance by a TV operator is a complex task because there are many parameters out from different parameter groups (Table 1). The scene parameters make up the contents of the image. System parameters comprise the flight and screening, transmitting and presenting of the TV data. Operator parameters are characteristics of the TV operator. Some arbitrary, task variables can be also attached to this group. Parameters of all categories are interrelated in a complex way. There are many studies about the cited parameters. Some of them are quoted in the last column of Table 1.

In RPV reconnaissance missions the operators have to interprete the transmitted data on-line. High speed and low level flight is a military demand for RPV. Therefore, viewing time had to be limited in our experiments with static scenes. We studied only the detection not the identification performance.

Investigating the search process researchers present more and more natural scenes because they recognized that structure and meaning of natural scenes affect the strategy and performance of the observer /1/ -/3/. It is insufficient e. g. to specify a line resolution for 50 % detection rate if one does not specify the territory too from which experimental scenes were taken. In order to study the importance of the target surroundings we included variations of context in our experiments. One must differentiate between immediate and total surroundings (local and global context).

For high presentation rate of different scenes the speed of processing of visual information is a limiting factor in real time reconnaissance, anyhow. It can be therefore assumed that the number and the configuration of targets play an important role for detection performance. For this reason we investigated these parameters.

There are several aids for target detection, e. g. scene arrangements which improve the search strategy. The question had to be answered if image partitioning facilitates the target detection or not.

2. METHODS

PARAMETERS

We investigated the parameters of Table 2 in 6 experiments. Different line resolutions were realized by presenting scenes with sizes reduced to different levels on the monitor. The viewing angle was kept constant thereby (Experiment 2). Manipulating the video signal, sections of the image were concelled (Image segmentation, Experiment 3). The contrast variation was carried out by taking advantage of the different model reflection coefficients and, additionally, by painting the vehicles with different colours, i. e. different

Scene Parameters	Target	Size	/4/
		Shape, Type	/5/
		Colour	/6/
		Number	/7/
		Configuration	/2/
		Motion State	/11/
	Target-Background	Contrast	/9/
		Context	/2/
		Target Position	/10/
	Environment	Terrain	/3/
		Scale	/11/
		Luminance	/12/
		Vegetation	/5/
		Colour	/13/
		Haze	/12/
		Sun Angle	/14/
		Sky/Ground Ratio	/12/
		Season	/5/
System Parameters	Aircraft	Height	/7/
		Velocity	/11/
		Yaw, Pitch, Roll	/15/
		Vibration	/15/
		Slant Range	/16/
	TV	Resolution	/9/
		Sensor Range	/15/
		Depression Angle	/17/
		Aperture Angle	/18/
		Spectral Range	
		Signal/Noise Ratio	/4/
		Bandwidth	/15/
		Codes	/19/
		Frame Rate	/16/
		Display Size	/9/
		Display Shape	/20/
		Flicker	/21/
		Screen Decay	/22/
Operator Parameters	Task	Real Time	/23/
		Aids	/20/
		Stereoscopy	/24/
		Team	/25/
	Physiology	Acuity	/20/
		Useful Visual Field	/26/
		Contrast Sensitivity	/27/
		Local, Temporal Integration	/27/
		Adaptation	/27/
		Colour Vision	/27/
		Eye Movements	/28/
	Cognition	Presentation Time	/29/
		Training	/30/
		Experience	/20/
		Search Strategy	/3/
		Pattern Recognition	/31/
		Decision Criterion	/32/
		Memory	/13/
		Motivation	/31/
		Social Context	/33/

Table 1: Parameters which influence detection performance of a TV operator.

reflection coefficients (Experiment 4). The configurations were divided into linear and random ones with contrast, approximate position and range being the same (Experiment 5). Local context was defined as structural camouflage of the targets within their immediate surroundings. Level 1 of local context was structural similarity between target and immediate surroundings (e. g. a vehicle being parallel to the nearby street) or proximity between them (e. g. a vehicle close to a bush). Level 2 was the reverse of level 1 (vehicle and street at an angle of 30 - 60° or a distance of several meters between them, Experiment 5). The number of targets was altered by presenting 1 scene at 4, 2 scenes at 2 or 4 scenes at 1 target. Scenery and positions were the same at all levels of target number (Experiment 6).

SCENES

Static scenes were taken as slides from a 1:87 terrain model with 4 summer-sceneries: forest, meadow, soil, village (Figure 1). A scene consisted of one of these sceneries and covered a ground area of 130 x 130 meters at a simulated altitude of 300 meters with vertical aspect angle. The slides were taken from diffusely illuminated scenes. The targets were military vehicles of 4 types: 2 different types of tanks, 2 different types of trucks. A scene contained 0 - 5 targets at a target uncertainty of 50 %. The targets were positioned according military demands.

APPARATUS

The slides were either scenes or a neutral pause picture. They were scanned by a TV camera and presented on a standard 625-line television with 38 cm screen size. The viewing distance of the operator was controlled by means of a head-rest. The viewing angle was about 20° (except in experiment 5 where the visual angle of target was examined). The subjects marked each detected target with a light pen and then switched off the scenes by pushing a button. A timer was stopped in order to get the search time.

SUBJECTS AND PROCEDURE

To examine the 9 parameters of Table 2 a series of 6 experiments with 1, 2 or 3 factors was performed with 19 untrained male subjects. The subjects were schoolboys and college students with a Snellen visual acuity of 1 or better. In balanced incomplete-block designs the parameters and their levels were combined so that each scene was presented to a subject not more than twice (at different parameter levels). Memory effects were avoided by turning the slides. In each experiment each subject observed each of the 4 sceneries the same number of times.

At the beginning of session the subjects read instructions indicating the nature of the detection task. They familiarized themselves with models of the 4 targets. A series of 10 training scenes was shown to each subject with feedback. Real time conditions were simulated by restricting the maximum viewing time to 4 discrete levels from 1 to 10 secs in each experiment. The levels and the examined parameters were balanced simultaneously.

The investigated dependent variables were detection rate, false alarm rate, search time, and the subject's confidence about his detection. After locating the targets, the subjects could switch off the scene before elapse of the maximum viewing time mentioned above. The timer was stopped simultaneously with erasing the scene. Thus the search time was the actual viewing time and there was only one search time per scene (not per target). There are two possible strategies of the subjects, either a) Erasing the scene early without searching thoroughly or b) Making the best of maximum viewing time without trying to stop earlier.

No of exp.	Parameters	Definition	Dimension	Levels
1	Maximum viewing time*	Maximum presentation time of the scene	sec	1, 3, 5, 10
2	Line resolution	Number of TV lines covering 1 meter of territory	lines/m	1, 2, 3, 4, 5
2	Global context*	Total surroundings of the target (different sceneries)	-	forest, meadow, soil, village
3	Image segmentation	Dividing the image and presenting the parts one after the other in equivalently reduced viewing time	-	1, 1/2 horizontal, 1/2 vertical, 1/4
4	Contrast*	$\mid \log L_o/L_s \mid$, L_o = luminance of object, L_s = luminance of immediate surroundings	-	0...0.2, 0.2...0.4 0.4...0.6, 0.6...
5	Local Context*	Local proximity or structural similarity between target and immediate surroundings	-	similar or close, neither similar nor close
5	Configuration*	Arrangement of a group of targets	-	linear, random
5	Visual angle of target	Visual angle of target width on the monitor	min	23, 32, 53
6	Number of targets*	Number of targets in scene	-	1, 2, 4

Table 2: Parameters tested for influence on detection performance. With * indicated parameters were varied in the other experiments too where they were not analyzed, however.

By asking the subjects to be quick as well as accurate, it was hoped to avoid uncertainty of the subjects' reactions mentioned above. Confidence was quantified by: 1 (no confidence), 2 (medium confidence), 3(high confidence).

3. RESULTS AND DISCUSSION

MAXIMUM VIEWING TIME

Figure 6 shows that detection rate D increases with maximum viewing time asymptotically like the cumulative probability of detection for unlimited viewing time /34/. A t-test by pairs revealed statistical significant differences for D(1 sec) - D(5 sec) and D(1 sec) - D(10 sec), $p < .05$. There is an increase in detection rate between 1 and 5 secs but the largest gain is obtained in the first second. False alarm rate was not influenced by maximum viewing time. Search times were nearly equal to maximum viewing times if it did not exceed 5 secs. At maximum viewing time of 10 secs the search time was only 6.3 secs. From this one can conclude that subjects try to chose an area of about $130^2 m^2 : 6.3 \approx 50^2 m^2$ as unity for search to get an optimal performance.

Taking the confidence levels into account the ratio D/FA increases from 1.6 to 2.2. Therefore, if persons have to make more or less uncertain decisions, as it is the case in real time reconnaissance missions, it is profitable to record confidence levels of the subjects and to weight the results of measurement with them.

LINE RESOLUTION

Detection rate depends significantly on line resolution (Figure 6). With increasing resolution more details become visible. This facilitates to distinguish targets from surroundings. Detection in natural scenes seems to comprise classical detection (finding something) as well as recognition (identifying something). Detection requires a search process, recognition is based on distinction between objects by means of cues.

False alarm rate increases drastically for a line resolution of between 2 and 1 line/m (Figure 7). A resolution of 1 line/m corresponds to a line resolution of 3 lines per target width; in this case only few cues can be identified. Subjects have to guess frequently so

that a lot of nontargets were marked.

Line resolution and all following parameters did not influence the search time averaged over all maximum viewing times. The strong limitations on search times by generally short maximum viewing times provoked the search time be independent of any other parameters.

GLOBAL CONTEXT

Figure 6 shows that detection rate depends strongly on global context. In village scenes only 27 % of the targets were detected. Targets are difficult to find in the village because both contain low and high spatial frequencies.The structural effects compensate increasing detection rate due to high contrast of village streets. In forest scenes 92 % of the targets were detected. In those scenes subjects did not need to scan the forest itself because of the absence of low spatial frequencies. Moreover, vehicles could not appear in this dense forest. The consequence of this is that the subjects inspected only the forest street and edge of the forest (as the questionnaires revealed). Therefore, nearly all targets were detected.

The difference of detection rate according to global context is pronounced at low level of maximum viewing time. There was no interaction between global context and line resolution.

The order of sceneries in terms of complexity as judged by subjects did not agree well with detection rate (r = .35). It is obviously not only the complexity, e. g. in terms of spatial frequency, which influences the detection performance but also knowledge about the contents of the images.

False alarm rate decreased clearly between experiment 1 (29 %) and experiment 2 (12 %) as a consequence of the training. It remained at low level until the last experiment. False alarm was independent of global context. Scale and line resolution were large enough to prevent confusion between targets and nontargets, but viewing time was too short to allow detection of all targets.

IMAGE SEGMENTATION

In experiment 3 image segmentation was studied. The parts were presented one after the other. Maximum viewing time was kept constant for the sum of the parts. Figure 6 shows that the degree of segmentation did not affect detection rate whereas the manner of segmentation did. In terms of detection rate vertical segmentation was superior to horizontal. The book page form of the vertical parts would support a search strategy like reading. Therefore a preference for linewise scanning can be assumed.

False alarm rate was again at low level (8 %). False alarm was given the least when presenting the entire image (Figure 7). More context provides more reference objects for the correct estimate of the critical ones (target or nontarget?).

CONTRAST

Contrast values in natural scenes are nearly continuous. For this reason detection rate had to be plotted as frequency distribution against contrast C (Figure 6). Detection rate increases asymptotically up to $C \approx .5$ which corresponds to a luminance ratio of about $L_U/L_S = 3$ respective 1/3. Higher contrasts did not yield a better performance. The high variance of detection rate is a result of the integrative nature of the measuring method (Figure 4). Structures which were fine but still resolved on the TV monitor were not registered by photometer. Therefore it happened that a target with C = .0 was always detected!

LOCAL CONTEXT

Local context, configuration and visual angle were studied in the 2x2x3 design experiment 5. Influence of local context was highly significant (Figure 6). Targets with structural similarity or close distance to their neighbouring objects (level 1) were detected less frequently than the others (level 2). Differences in detection rate depending on the local context were strongly pronounced at low maximum viewing times of a few seconds. Short presentation times allow only few fixations. In this case, portions of the display could only be considered with the lower acuity of peripheral vision. An observer who looked at the right hand side of the scene saw a target on the left hand side at an angle of 20^0 extra-foveal where acuity declined to 10 % of the foveal one. With this acuity value subjects could only differentiate distances and angles between target and neighbouring objects which occured only for level 2 of local context.

False alarm (on average 12 %) was given more frequently at level 1. It is surprising that a variable which refers to nontargets (false alarm) is influenced by a parameter which refers to targets (local context)! This can be interpreted by regard to the subjects' reactions. The sum of markings is constant for level 1 and level 2. They try to mark similarly frequently in different scenes. There are fewer correct detections at level 1 of local context (as mentioned above) but more wrong ones instead of it.

CONFIGURATION

In linearly arranged target groups all targets were detected more frequently as in randomly arranged groups, whereas in these groups at least one or more targets were detected more frequently. But these effects were compensated so that on average detection rate did not depend on the configuration. In contrast to this, identification of groups do depend on the configuration /10/.

VISUAL ANGLE

The visual angle did not influence detection rate. This result confirms the findings of Williams '66 /8/ according to which screen size does not affect detection performance. Distances were always shorter than the range of visual resolution of TV lines (~ 4 times screen diagonal line)). The subjectively agreable viewing distance was about 2.5 x screen diagonal as a separate test revealed.

There were no interactions at all between local context, configuration, and visual angle.

NUMBER OF TARGETS

Though there were the same maximum viewing times for each level of target number, detection rate decreased only slightly for higher values. It has to be remembered that each detected target had to be marked by light pen (detection related to targets, Figure 6). Effective search times were identical if the pure times for marking are subtracted(N = 1 : .8 sec, N = 2 : 1.2, N = 4 : 1.9) from the measured search times. It can be concluded that scenes are searched regardless of their target number for at least one time and equal frequently.

Still another dependency can be found if one analyzes the data of this experiment in view of the question: "Are there targets in the scene at all?" One detected target is now sufficient in order to say that the scene contains targets (detection related to scenes). This modified detection rate increases clearly with number of targets since it is more probable to detect any target of four than detecting exactly the only one existing (Figure 6), /1/. Thus, the influence of the number of targets or detection rate depends strongly on the military demand which can be either to detect each target or just to detect the existence of enemies generally.

No of exp.	Source of Variance	df	F-ratio	$F_{Critical}$	Probability Level
1	Maximum viewing time	3	1.54	2.2	NS
2	Line resolution R	4	10.5	3.4	< .01
2	Global Context G	3	66.5	3.9	< .01
3	Image partitioning	3	2.5	2.3	< .1
4	Contrast	3	66.8	3.9	< .01
5	Local context L	1	61.5	8.7	< .01
5	Configuration C	1	.1	3.1	NS
5	Visual angle V	2	.1	2.7	NS
6	Number of targets	2	3.1	2.4	< .1
2	RG	12	1.3	1.6	NS
5	CL	1	.1	3.1	NS
5	CV	2	2.5	2.7	NS
5	LV	2	1.4	2.7	NS
5	CLV	2	2.1	2.7	NS

Table 3: Summary of analysises of variance for detection rate.

QUESTIONNAIRES

After each session subjects filled in a questionnaire to give information about their strategy, mental load, and the comfort of handling the apparatus. The results were:

- Subjects became more and more conscious of their search strategy.
- Subjects searched systematically (63 %), in dependence on the scene contents (42 %), with a orientation phase at search beginning (37 %), areas with good target-background contrast above all (26 %).
- The marked hole of one of the two types of tanks was an effective cue for its detection.
- Rectangular objects e. g. houses are easily taken as targets in search for targets.

- A complete search of the $20^o \times 20^o$ scenes takes 2 sec. Number of search passes are proportional to the search time.
- The concentration of subjects increases with decreasing maximum viewing time.
- Maximum viewing times below 3 secs impose stress.
- The demanded decision criterion "Be quick as well as accurate" is not followed. 58 % of subjects try to be accurate.
- Motivation is stimulated by interest and payment, not by a bonus for good performance.
- Quick location in static scenes is done comfortably by light-pen.
- Viewing distances below screen diagonal length disturb subjects.

4. CONCLUSION

Figure 8 presents a statistical comparison of all examined parameters. The columns present the percent portions of variation in detection rates η^2 attributed to the parameters p_i: $\eta^2 = (SS_{pi}/SS_{total}) \cdot 100$ % (SS = sum of squares). The relatively greatest influence on the detection rate have scene parameters which constitute the conspicuity of a target in natural scenes: Global context (η^2 = 77 %), contrast (57 %), and local context (24 %). The system parameters image partitioning (20 %) and line resolution (16 %) have a smaller influence on detection rate. η^2 of maximum viewing time, number of targets, visual angle, and configuration are all below 10 %. The worth of the η^2-comparison is restricted since η^2 is a descriptive measure in the specially chosen sample. Moreover, variation depends on the parameter ranges which are incomparable because of their different dimensions. One has to remember these limitations regarding e. g. the low orders of maximum viewing time and visual angle. But there is no doubt that detection performance is affected by scene parameters which can be influenced not at all (context) or only very little (contrast) by reconnaissance party. The effects of the variable system parameters (image partitioning, line resolution) had to be cumulated to affect detection performance remarkably. Maximum viewing time plays a role at the low levels of 1 and 2 secs. Therefore, with increasing speed of the RPV the effect of the viewing time will be added to that of the parameters mentioned above.

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6. ACKNOWLEDGEMENT

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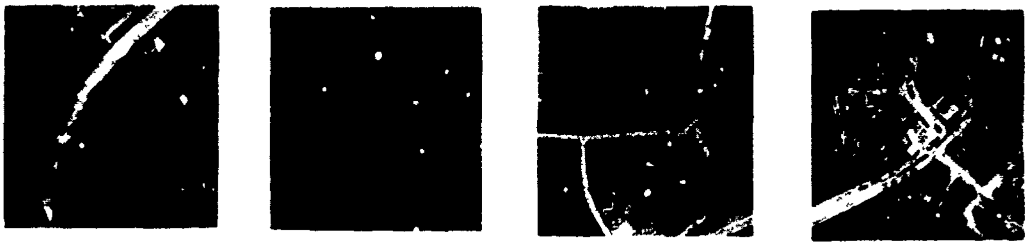


Figure 1: The 4 different sceneries used in experiments 1 - 6: forest, meadow, soil, village.

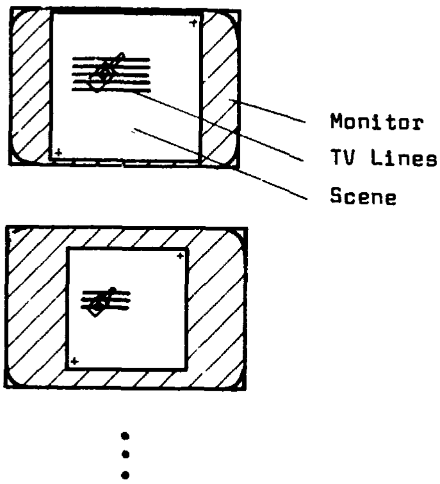


Figure 2: Simulation of Different Line Resolutions by Varying Scene Size and Keeping TV Norm.

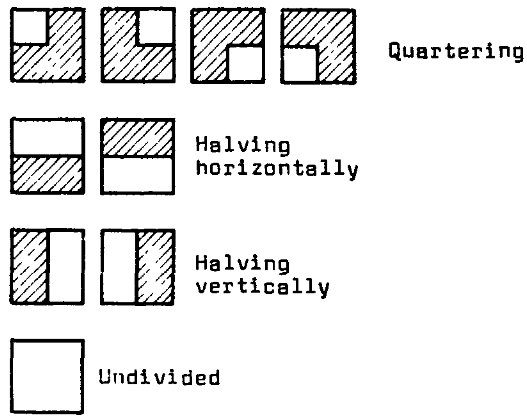


Figure 3: Principle of Image Segmentation.

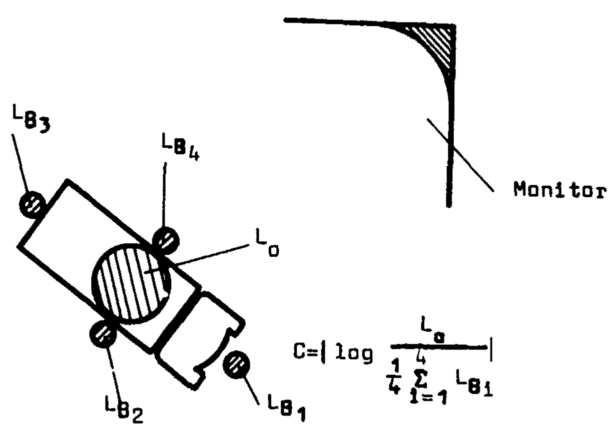


Figure 4: Measuring Method for Contrast.

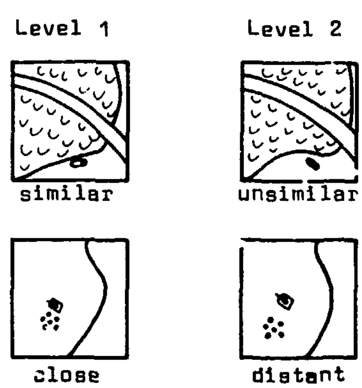
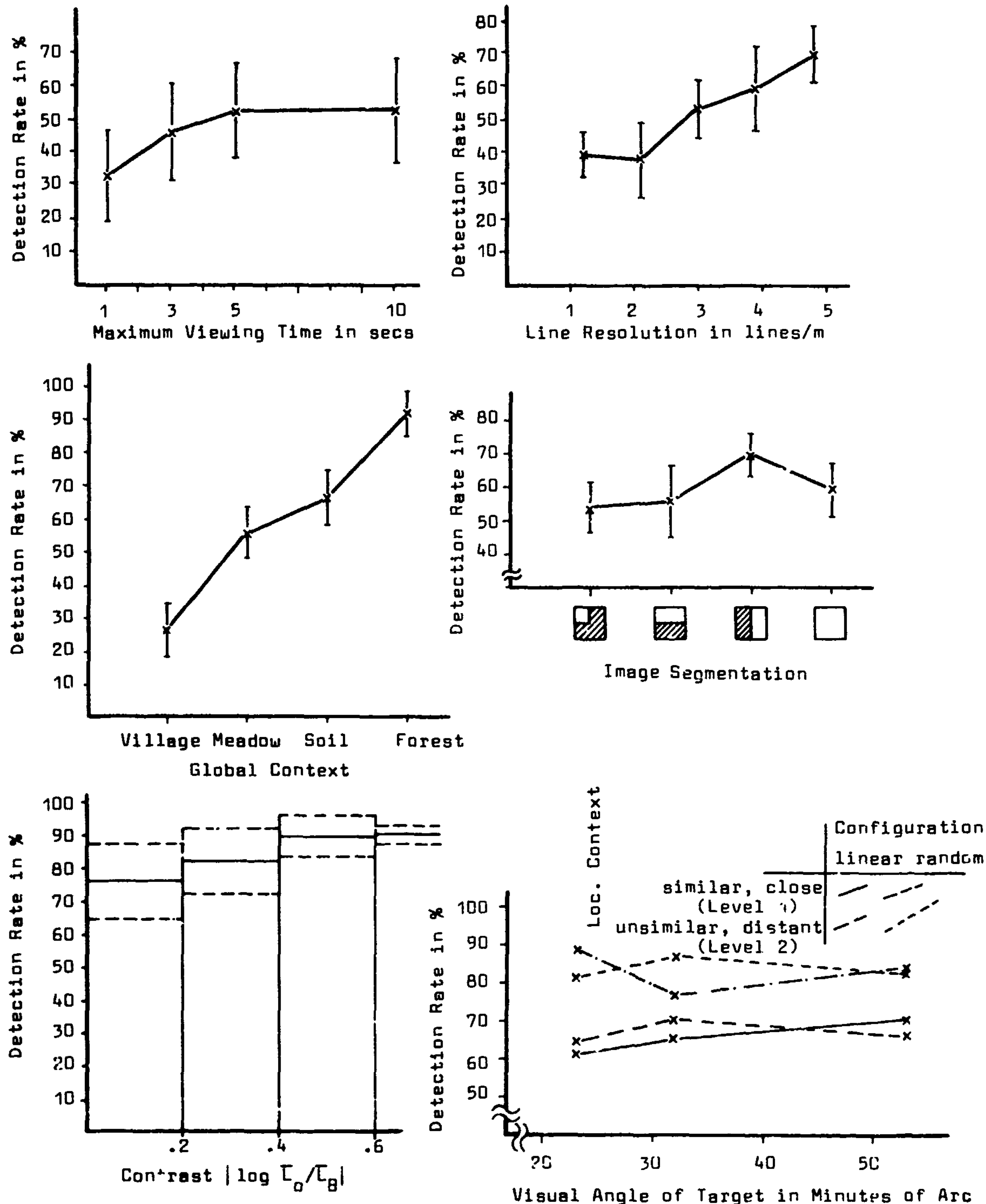
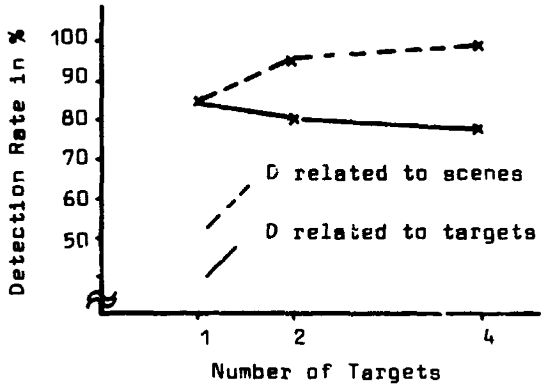
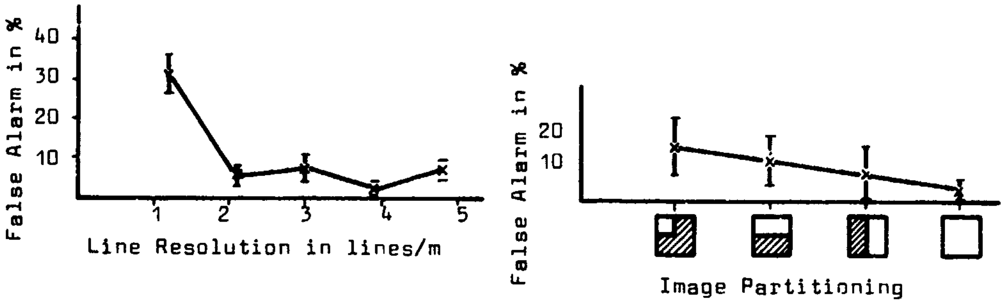


Figure 5: Arrangements of Targets for different levels of local context. Level 1 = Structural similarity or proximity betw**e**en target and immediate Surroundings. Level 2 = Unsimilarity or distance.





igure 6. Detection Rate as a Function of Maximum Viewing Time, Line Resolution, Global Context, Image Partitioning, Contrast, Visual Angle, Local Context, Configuration and Number of Targets with .95 confidence intervals.



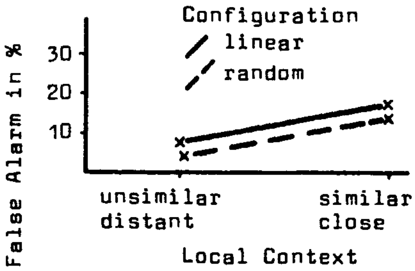


Figure 7: False Alarm as a Function of Line Resolution, Image Partitioning, Local Context and Configuration with .95 confidence intervals.

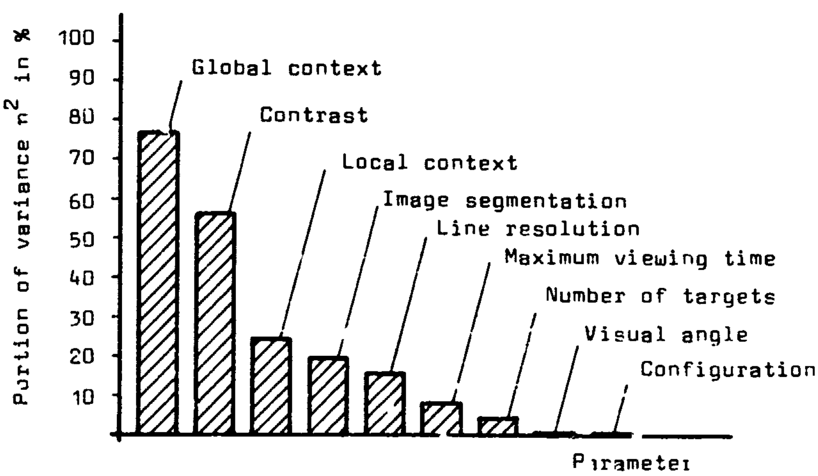


Figure 8: Portion of variance $\eta^2 = SS_{p_i}/SS_{total}$ (SS = Sum of squares) of detection rates in dependence on the examined parameters p_i.

DISCUSSION

H. PONGRATZ (FRG)

You showed that a resolution of 5 lines/m gave a detection rate of about 70% (*figure 6 of the text*). Would the rate continue to rise with increasing resolution, or would it fall off asymptotically? How many lines/m resolution would be needed to give maximum detection efficiency?

AUTHOR'S REPLY

The required resolution depends upon the task. If you want to discern objects which differ in details of length L (m), you need a line resolution of 1/L (lines/m). I was not at the asymptote, but for a rather good acquisition of military vehicles in natural scenes the literature recommends a line resolution of 12 lines/m.

THE INFLUENCE OF THE DESIGN OF DISPLAYS ON COCKPIT WORKLOAD

by

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Summary

This paper discusses the problems involved in designing displays and controls for high speed low level aircraft with the reduction of cockpit workload as a prime consideration. The cramped confines of fighter cockpits together with the expanded operational capabilities possible with modern sensors leads to the conclusion that the displays must be multi-function. Control of the avionics under combat conditions requires a high degree of automation; nevertheless the crew must be able to manually control the systems with a minimum number of switching operations. Brief descriptions of some modern display techniques are given with emphasis on their workload reducing attributes and the paper concludes with the view that the effectiveness of future aircraft will depend largely on the mission-crew-avionic interface and that this must be an essential part of the overall cockpit design philosophy.

1. Introduction

The difficulties which occur when flying at high speed and low level are exacerbated when in-flight visibility is reduced by weather or bad light. Avionic systems can contribute greatly towards overcoming these difficulties through the display of navigation, sensor and weapon data. However, the operation of many current aircraft avionic systems impose very high crew workloads and it is essential that the crew is not denied the effectiveness that could come from future avionics because the systems are too difficult to operate. Thus the crew-system interface must be considered at the design stage and reflect a system operation logic which is standardised throughout the cockpit. The controls through which the crew communicates with the avionics must be simple to operate and the displays must be easy to read under the stresses of combat conditions. Because the displays could arguably, swamp the crew with data it is essential that crew workload is considered during their design, that only clear essential data is presented and all that is superfluous to each part of the mission is excluded. In other words the data presented should be matched to crew workload with display format and content optimised for the crew-system interface. This leads to the conclusion that the displays should be multifunction and capable of format reconfiguration to cater with the ever fluid tactical situation together with future changes in threat, mission and sensor developments. Such flexibility is an inherent characteristic of electronic displays and will be an important feature of future cockpits.

2. Workload

There have been many attempts at a definition of "pilot workload" none of which has proved universally acceptable. Similarly there have been numerous practical experimental programmes to try to assess what constitutes workload. These, as with most tests involving inherently variable human beings have yielded results which, if nothing else, indicate that different people at any one time or even the same people at different times do things in many different ways and that quantifying workload is no easy task. With this background of failure by those infinitely more learned than myself it would be presumptuous to try to define overall pilot workload so I shall confine myself to the subject of how easy it is for a pilot to communicate with the avionic systems through his display controls and suggest how the types of displays can be organised so that he can easily gain the information he needs from them.

It is instructive to note how a pilot gains information in flight by using his visual, aural and tactile senses - see Figure 1. Of the three, the visual channel clearly is vital and has the largest number of inputs but information gathering is a high speed process with rapid correlation of data while aural information gathering is low speed with slow sequential input of data. The tactile channel is not overloaded, tactile warnings are rarely used and although the aircraft must be flown, systems controls can be operated at the same time whereas it is not possible to look at two things at once nor to reliably take in two simultaneous audio signals. It is clearly undesireable to further overload the visual channel by requiring its use for systems control operation. A point I will expand on later.

The process by which man makes decisions based on these sensory inputs can be likened to the operation of an avionics computer as shown in Figure 2. However, while man's long term memory has immense capacity and is his greatest strength, his short term memory is notoriously unreliable and his single decision channel lacks the high speed of the computer. These factors are of prime importance in the design of controls and displays.

3. Controls

The small size of fighter cockpits when combined with the large number of aircraft systems each with their associated control panel leaves little space for the controls and displays with which the pilot interacts with the avionics. a situation which is exacerbated if his reach and vision is impaired by the constraints of a reclined high 'g' seat. There is a strong temptation to reduce the panel area requirements by using multifunction controls and in theory it is possible to control all of the avionics through one multifunction panel. By multifunction I mean that one control has many functions depending on the operation of some previous control, as shown in Figure 3. This, although a neat engineering solution to the problem of lack of area, is fraught with problems from the point of view of workload. One of the

important factors in fighter operations is that most of the short term inputs received by a pilot come from outside the cockpit through his vision. These include terrain, obstacles, orientation, other aircraft, ground targets, hostile fire and the head-up display. Conversely most of his long term inputs come from inside the cockpit through radar, sensor, navigation and map head-down displays. In both cases he will need to operate controls at the same time, and where possible these operations should not divert his attention from the visual input.

Thus the controls associated with displays should be adjacent to them. Since displays need to be orientated approximately normal to the pilot's line of vision they will usually be on the main instrument panel rather than on the side consoles. As such they will tend to be at arms reach which makes for difficult operation under 'g' or turbulence, where double entries or failure to enter data are common.

After a relatively short period of familiarisation with a cockpit most pilots when blindfolded are capable of identifying by touch all of the controls. Where these are single function controls he can also operate them by feel. In this he relies on his long term memory and spatial co-ordination. However, when these controls are multifunction his short term memory is involved and being poor it nearly always has to be augmented by vision. In this case he needs to have visual feedback from the associated display immediately next to the controls so that he does not have a large time consuming visual scan angle from the control to the display. To operate a keyboard by touch is not too difficult when each key has only one function but when multifunctioned the task becomes very demanding. To give a very simple example, a four digit radio frequency selector can be reset by touch without visual augmentation either by resetting each digit to zero and counting the clicks or by remembering the original frequency and incrementing or decrementing it as appropriate. This can be a very difficult task when one is occupied with controlling the aircraft and virtually impossible if one has to return to it at the half way point following an interruption when the stage one had previously reached is easily forgotten. However, the process becomes very easy when augmented by immediate visual feedback. The same holds true of most multifunction controllers unless complicated data insert logic is involved.

It has been stated that retention of short term memory may be as low as 3 seconds. After this time there is a 50% chance that items of information may be forgotten especially in high workload conditions. After about 18 seconds there is only a 10% chance of remembering data when working on a simple task.

The essential problem, however, is that the pilot must look at a multifunction controller while operating it which denies him short and long term outside world and sensor inputs for the period. The consequences of this obviously vary according to the situation. If heavily involved in manual high speed very low level flight one cannot afford to look in at all hence all control selections must be by touch. If involved in visual air combat, looking in frequently causes one to lose contact with the other aircraft involved in the fight which would be disastrous. If flying head down on instruments, looking away to operate controls involves loss of instrument scan sufficient to cause significant deviations from the desired flight path. So, while there are powerful arguments for multifunction controls, there are even more powerful arguments for confining their applications to systems which are operated during periods when temporary loss of visual input from the outside world or flight displays is not crucial.

It is of interest that, for reasons of workload, manual input of data into the Flight Management Computer of modern civil airliners usually is effected through a full alphanumeric keyboard which has 26 buttons for alpha entry with a separate 10 buttons for numeric entry. For similar reasons slew controls and multifunction push buttons for data entry were consistently rejected as unsuitable during pilot assessment of the BAe Weybridge Advanced Flight Deck (AFD) Simulator. While commercial pilot workload is quite high, given that there is at least one other pilot to share the load and that virtually the whole flight is on autopilot, the task cannot compare with the difficulties of the pilot at a single seat fighter. Even those controls which are single function and hence only require touch operation are affected by operational constraints. For example, although it is easy to identify controls by touch when seated normally it is another story when twisted around looking backwards at the opposition or when pulling 'g'. Then the only controls one can be sure of operating are those on the throttle and stick - the HOTAS concept. It is of interest that the F-16 has some 370 dedicated switch positions of which 16 are on the stick and throttle and only about 10 multifunction switches associated with the stores management system display.

One proposed solution to the problem of physically operating controls under high workload or 'g' conditions is to use Direct Voice Input (DVI). My company is currently engaged in research into this subject using several approaches. Broadly speaking their research shows that a subject whose voice pattern has been previously given to the equipment can achieve about 90% success in giving simple commands by DVI. They predict that higher levels of success are likely but that it will be many years before DVI will be sufficiently reliable to carry out any flight-critical cockpit switching functions.

In the near future DVI could be used as an "add-on" extension to existing switch systems but the basic switches must remain in being to give completely reliable functioning plus visual and tactile confirmation of selections which have been made.

A further consideration is that the radio is very busy in fighter operations, and the aural channel is already overloaded. When not transmitting, pilots must listen out for other calls hence voice communication with one's own aircraft could lead to missed radio calls from others. This, for example, happens more frequently in two seat aircraft where intercockpit voice communication is used than in single seaters where it is not,which indicates an important operational disadvantage of DVI. In addition the system operates in a similar way to multifunction keyboards in that a set sequence must be followed to reduce the size of vocabulary for each phase and thereby increase the probability of correct recognition. For example to change UHF frequency it may be necessary to say Radio - UHF - 236 point 2, and this sequence must be correctly followed Under the stress of combat it may be difficult to follow this ordered sequence using the same calm tone of voice that was used when initially feeding one's speech patterns to the system.

Nevertheless DVI has considerable development potential as another communication channel between pilot and aircraft which might ultimately overcome the physical reach constraints associated with conventional cockpit switches.

To summarise, pilots have very little spare sensory capacity for systems management when at high speed and low level and if the full potential of modern avionics are to be realised they must be easy to control and be highly automated.

4. Displays

Displays are the means through which the avionic and aircraft systems present data to the pilot. There is enough space in the average single seat fighter cockpit for a small radar display and conventional flight instruments but when further sensors are added or the possibility exists that they could be added in the future, a solution to the problem of space is to integrate data into smaller groups and portray it on electronic displays.

In the civil display field it is proposed to integrate the flight instruments into a Primary Flight Display, navigation and weather radar into a Navigation Display, all engine data into an Engines Display and to also have Systems and Warnings displays. For military aircraft, sensor and weapon aiming displays would also be required making a total of seven surfaces. Clearly this poses problems of lack of available space and for this reason plus the need to cater for display surface failure, the displays must necessarily be multi-function. This implies that some data will not be continuously displayed and that the display formats will perforce be mode-dependent.

It is tempting to take the view that the ability of electronic displays to draw any shape of symbol creates an opportunity to radically change the traditional display formats for such parameters as attitude, altitude etc. For example, mechanical constraints have limited the format development of electromechanical attitude indicators to a ball-type presentation with different colours for above and below horizon indications, whereas electronic displays do not have this restraint.

An attitude display has to fulfil two quite different requirements. First it should be possible to recover from unusual positions, for example a steep inverted climb, by immediately assessing what is the quickest, safest action to regain wings level horizontal flight. This requires a coarse scale with strong upright/inverted cues. Pitch and roll rates will be high and the total picture must be available, instantly and unambiguously. Secondly there is the need for fine, precision attitude control during instrument approach procedures, IMC low level, or fighter interception procedures where pitch and roll rates are low. For these phases of flight a larger scale would be advantageous. A large scale presentation near the horizontal and a small scale presentation near the vertical is a feature of the F-16 HUD symbology and perfectly feasible for CRT Flight Displays.

However, there are strong reasons why an electronic flight display should be essentially similar in appearance to existing electro-mechanical units, at least to the extent that a pilot used to flying by dials can recognise the display for what it is, see Figure 4. Firstly, it is an earth referenced situation display hence it should include a horizon line and pitch reference augmented by bank and up/down cues. Secondly, for reasons of integrity of vital flight data some dissimilar standby instruments will be required and to some extent their formats will influence those of the electronic displays, since they should be alike so that it is easy to transfer from one to the other. Nevertheless, it is possible by integrating airspeed, altitude (baro and radio), attitude, bank, heading, flight path, potential flight path and ILS guidance into one CRT display to reduce the instrument scan time with consequent improvement in flying accuracy and reduction in workload.

Similarly, an integrated navigation display as shown in Figure 5 can reduce workload in two ways, scan time is reduced and the display can pictorially represent where the aircraft is in relation to desired route rather than as in traditional displays relying on pilot interpretation of position through bearing/range and a mixture of mental gymnastics and rules of thumb.

Whether it is necessary to display continuously all engine parameters is open to question. On the one hand automatic engine controls can reduce the need to display anything other than the dominant parameter, be it RPM, EPR or fuel flow. On the other hand if only one engine is fitted it is of such vital importance that visual access to its parameters should be more or less continuously available.

It is in the area of systems and warnings displays that the greatest opportunities for reducing workload lie. Currently the pilot is presented with a diversity of dials and lights many of which are of different scale and manufacture and not easy to interpret. For example the normal operating area on one dial may have the needle vertical, on others it may be anywhere. Consequently it is difficult to tell at a glance whether all systems are well and it is often necessary to remember many different numbers. In this respect light aircraft which have dials with coloured segments for normal or caution ranges often have better presentations than military aircraft.

Most aircraft systems have one or two primary parameters for example pneumatic pressure which give clear indications of their health. It may be sufficient to display only these parameters continuously while retaining the ability to call up a more detailed display of secondary parameters when required for checks or subsequent to a failure. It is also possible to inhibit warnings when these occur naturally as a consequence of a failure. In some twin engined aircraft the first indication of engine failure is illumination of the generator failure warning light followed by low oil pressure and the pilot can be triggered into inappropriate emergency drills. By rationalising systems and warnings the prime cause, engine failure, plus an indication of why it failed and the appropriate emergency drills can be displayed to the exclusion of the consequential failures.

It is virtually impossible to handle paper check lists at high speed and low level but perfectly feasible to carry out electronically displayed emergency drills. Confidence that failures will be disclosed reliably to the pilot can reduce his need to monitor systems and allow him to concentrate on his mission.

Weapon aiming will normally be carried out using a Head-Up Display (HUD) or Helmet Mounted Sight (HMS) where the target is outside the field of view (FOV) of the HUD. These are collimated displays which allow the pilot to see both target and display without the need to refocus the eyes thus achieving greater efficiency of visual data input through time sharing. It is likely that target acquisition will be enhanced through the use of some sensor other than the human eye and since the sensor acquisition period immediately preceeds visual acquisition it is vital that the transition between them is quick and positive. In fact the first contact may be visual, the pilot will acquire using the sensor, then having assessed the situation and formulated his tactics he will go head up again for the engagement. More than one sensor, e.g. radar and visual augmentation system may be involved. Thus there are strong arguments for also collimating the sensor displays as an aid to reducing the time needed for accommodation changes from head up to head down and vice versa. A collimated display of this type has been fitted to a simulator at BAe Warton, see Figure 6, and a smaller but essentially similar display is used in the SAAB Viggen. There are several other advantages in collimating head-down displays; a small display can be magnified to give larger IFOV through the use of binocular vision and the display is easier to read under turbulent conditions since the display format apparently moves up and down in phase with the pilots eyes.

4.1 Display Legibility

The open military cockpit is a very demanding environment for electronic displays. Unlike non-luminous conventional instruments whose legibility relies on reflected illumination, electronic displays depend on their luminous properties for legibility and as such they have to compete with ambient illumination. The two prime factors governing electronic display legibility are contrast and luminance. Essentially one only sees some thing because it contrasts with its surroundings hence this is an important factor to maximise. This is easily achieved with electronic displays by use of contrast enhancement filters which work on the principle that by limiting light transmission to say 10%, while the CRT brightness is reduced to 10%, the ambient illumination which has to pass through the filter twice is reduced to 1%. (Fig.7).

Filters which are wavelength selective can also be used, typically these are matched to the wavelength of the CRT phosphor which further improves contrast. Lower transmission filters will give greater contrast, but at the expense of display brightness. When a pilot looks out of the cockpit his eyes adapt to the bright outside world, and so when he looks in at his display he is not able to see low brightness displays as well as if his eyes were adapted to inside rather than outside light levels. Consequently there has to be a trade-off between contrast and brightness.

The next speaker will describe colour displays in some detail, and so I will ignore the topic except to note that colours have strong attention getting properties hence they should only be used for this purpose.

Highly coloured displays, whilst very pretty, probably have less information transferring qualities than where colour is used sparingly since the colour can be another superfluous item for the already overloaded visual channel to process. Too much colour could arguably increase workload, selective use will decrease it.

5. Cockpit Integration

In many jet fighters little attempt seems to have been made to place displays and controls where they could be easily read or reached. I could cite the Vampire fuel gauge, Hunter compass, Harrier radio and Phantom Weapon switches all of which are hidden behind the stick. Some aircraft had all the "once a flight switches" on the left console and within easy reach of the free left hand with the switches that need to be operated frequently on the right console which involved swapping hands on the stick.

Other early aircraft had poor systems integration with incompatibilities between different systems. This problem seems to be largely overcome, and indeed, the need for avionics to communicate on common data buses demands system compatibility.

However, it is only on the latest aircraft that the system integration process has spread to include the pilot. The F18 is a particularly good example. This aircraft has the same task as its predecessor the F4 but has only one crew member. Pressure from the operators was for two crew but this was ruled out on cost grounds. As a result extensive human factors work was carried out on the man-machine interface to ensure that the task was feasible for one man and the cockpit has been described as "as close to perfect as you can get". However, even this cockpit could be improved by the use of colour and more collimated displays.

The lesson is that avionics capability has outstripped pilot capability yet he is the key to success and must be considered at all stages of the design. The cockpit is more than an aerodynamic, inconvenience, it is the heart of the machine and must be tailored for his task. This fact places a large burden on the airframe designer who must have staff who understand the needs of the pilot and the nature of his task.

"Experience in the recent past has shown the extreme difficulties and indeed, flight safety hazards, which have occurred when system operation, functions and displays have been designed and evaluated without taking full account of the very demanding military flight environment. Simulator and other trials have often resulted in extremely logical and orderly lay out of controls functions and sequences. Unfortunately, they have often failed to relate the pilot's operation of these system controls and displays to the fact that he may very probably be flying under manual control at 100 - 200 feet at around 550 knots. Under these circumstances and others, such as I have described, the time and attention span, which the pilot can give system operation, is exceptionally limited and however elegant and logical the control and display functions provided, he will be unable to use them unless their operation can be made in a near instinctive manner and with the minimum distraction from the flying task.

I strongly believe that system control and display functions in the past have frequently been evolved on the basis of what is good for the system operation, rather than what is good for the overall flying task.

The real problems of survival and avoidance of terminal flight safety hazards in high speed low altitude flight and air combat/offensive operations, demand that for future aircraft we should always place the flying task as the main criteria and attempt to fit system operations to it. Unless we choose our priorities in this fashion we will continue to run the risk of producing exceptionally good systems which are incapable of use by the pilot at the time when he most needs their assistance."

6. Conclusion

In this paper I have attempted to show how considerations of human factors in the design of controls and displays can reduce pilot workload and improve operational efficiency. The high speed low level task is very demanding and the pilots visual channel in particular is heavily loaded. Consequently the pilot should not have to look at controls when operating them and displays should be capable of swift interpretation leaving the visual channel as free as possible for the vital outside world inputs. Collimated helmet, head up and head down displays can improve the visual data gathering process through eliminating the refocussing time delays and colour displays can reduce scan times through identifying the priority elements of the format. Human factors considerations throughout the design stages will improve operational efficiency and safety and help realise the full potential of modern avionic systems.

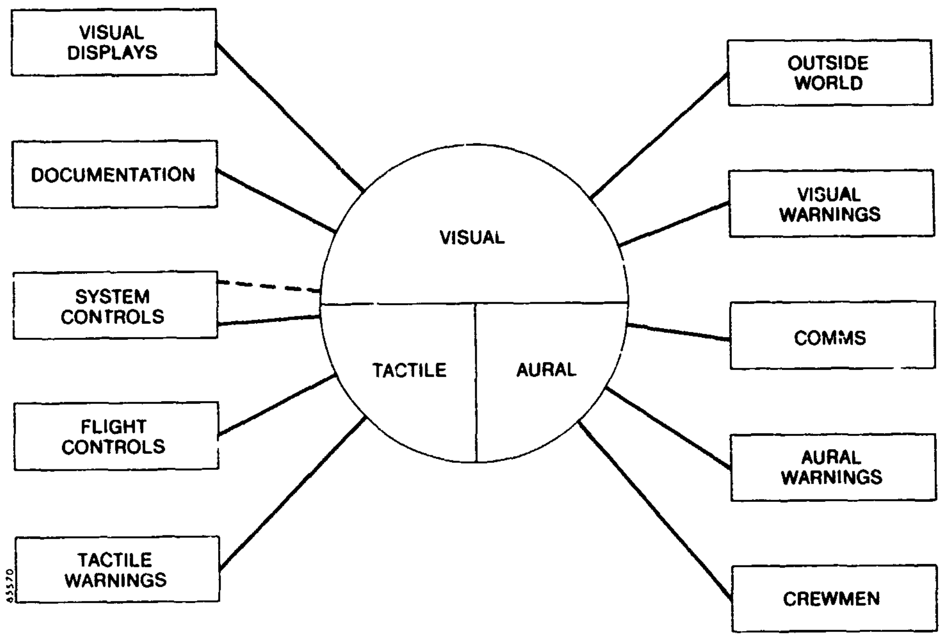


Figure 1 Sensory Inputs

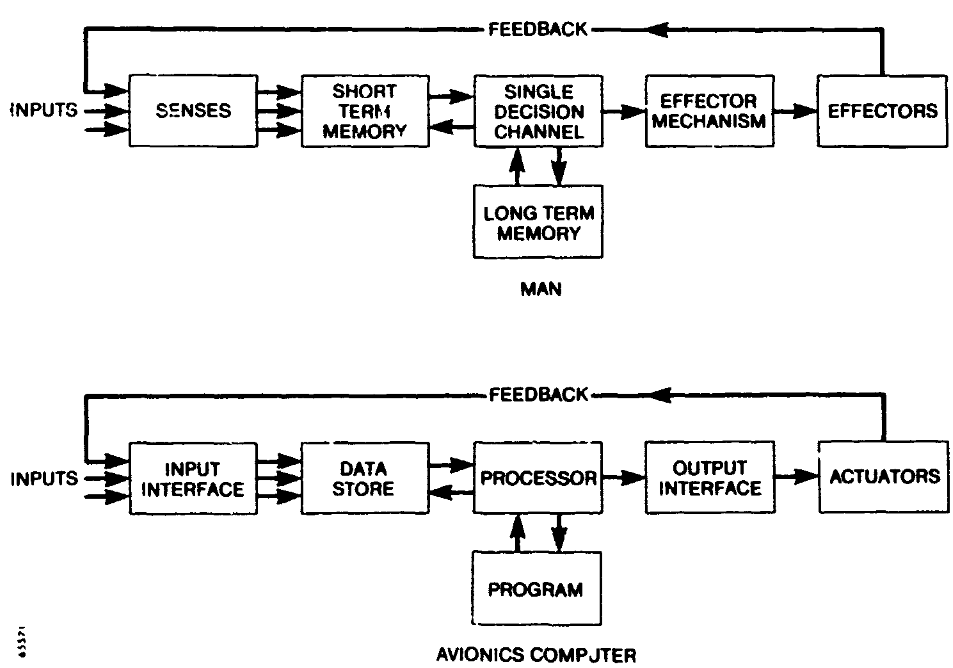


Figure 2 Decision Processing

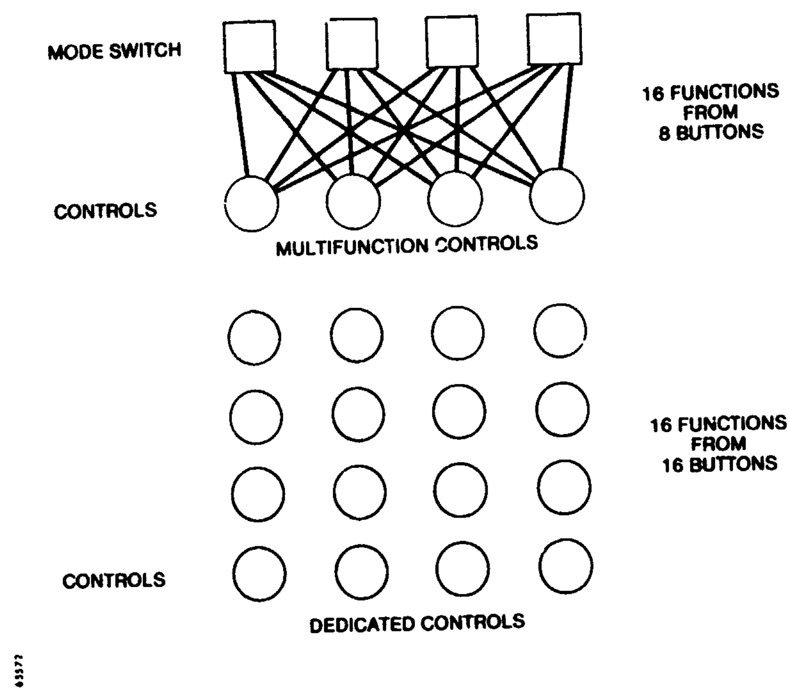


Figure 3 Controls

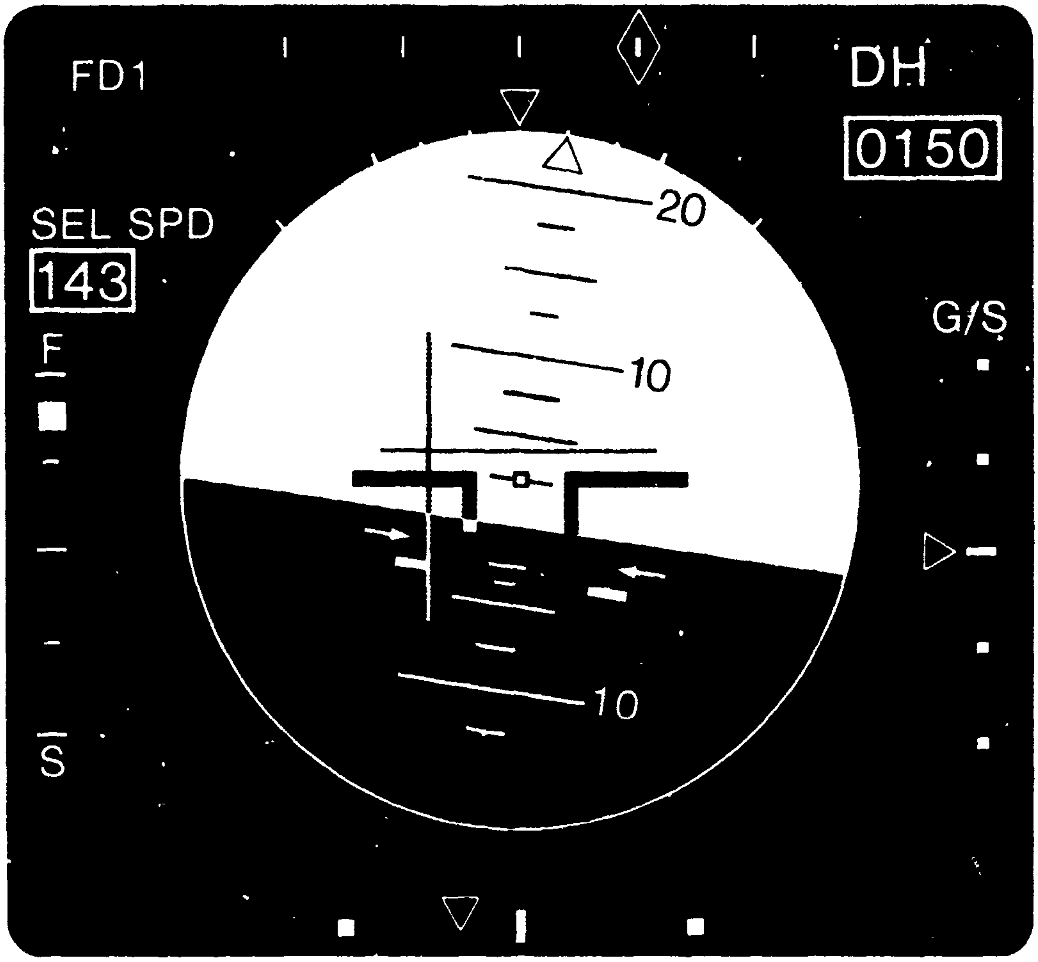


Figure 1   Primary Flight Display

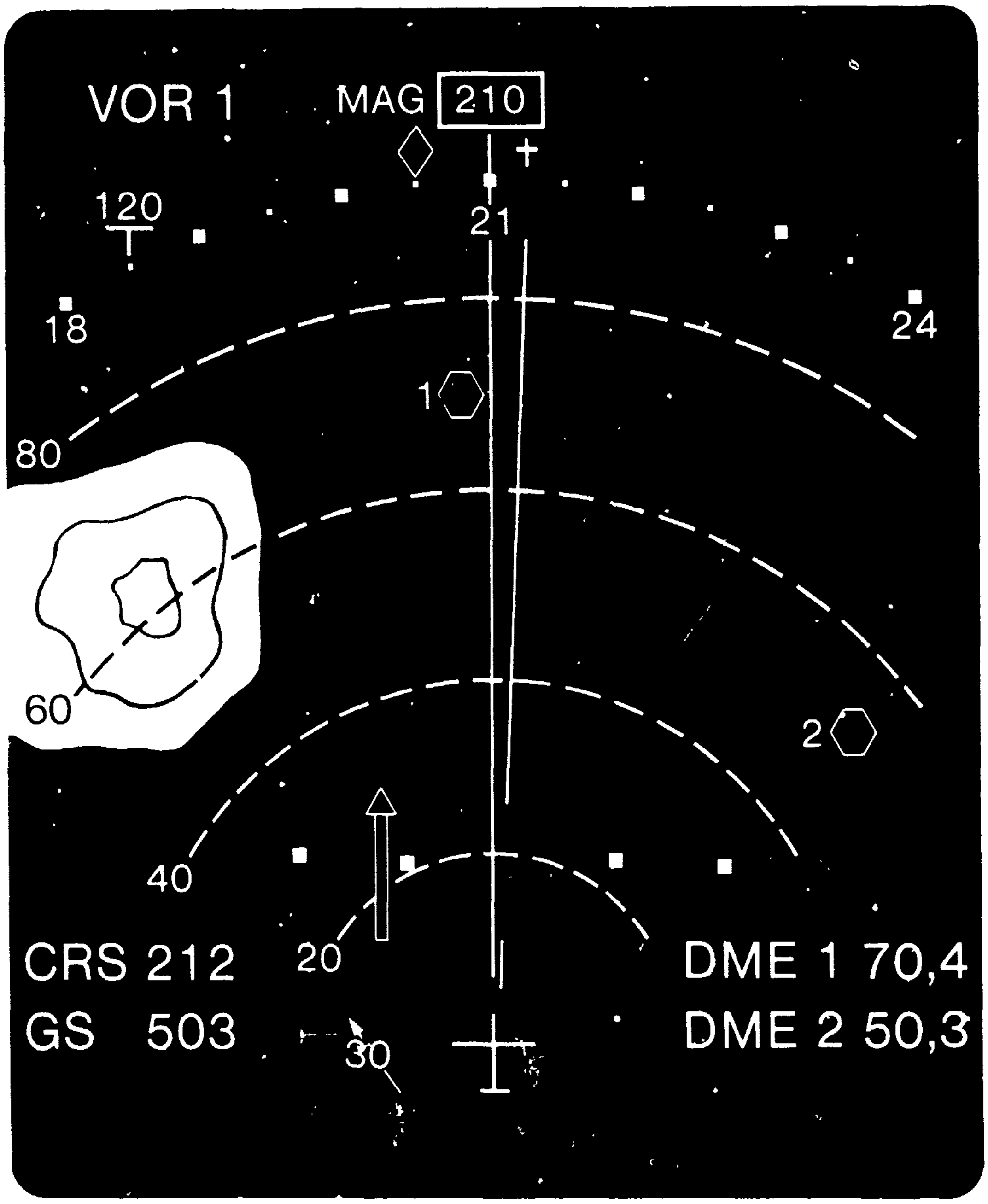


Figure 5. Navigation Display

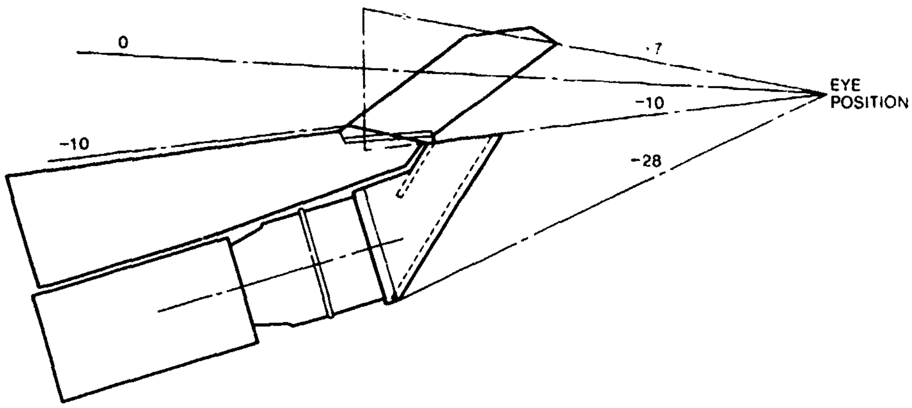
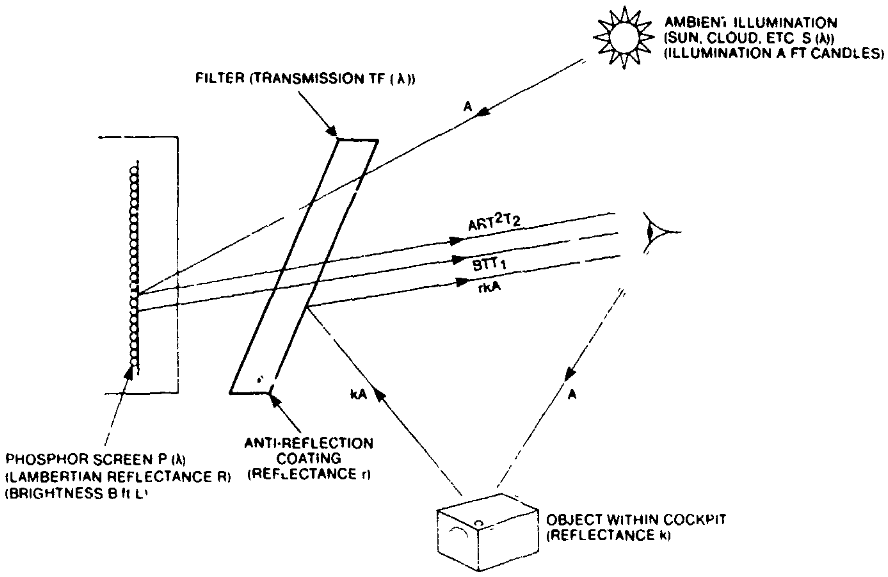


Figure 6 Collimated Display



NOTE FOR SIMPLICITY REFLECTIONS OF MINOR CONSIDERATION HAVE BEEN OMITTED

Figure 7 Optical Filter System

Colour Displays: Their Availability, Performance and Application to Improved Crew Efficiency

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Summary

High performance monochrome crt displays have proved both acceptable and even essential in efficiently presenting complex data to flight crew. Their usefulness is particularly enhanced by their inherent flexibility through re-configuration and operation as mode dependent multi-function displays. The experience and confidence gained with electronic display systems in modern military aircraft have contributed to the fact that the next generation cockpit is likely to make very extensive use of crt displays. In view of the primary and therefore critical contribution of crt displays to the mission task, it is essential that every reasonable effort is made to ensure that information is presented in the most easily assimilated form. A colour capability will undoubtedly help in this regard provided too great a penalty is not paid in other areas.

It now appears feasible to provide the aircrew with a display with full colour capability and a generally acceptable performance level.

This paper reviews the arguments governing the choice of technique, establishes the likely performance parameters and suggests guidelines that will be of use in determining how colour will be used to enhance the presentation of information.

1. INTRODUCTION

The thesis that the pilot is now both pivotal to mission success and, as a consequence, acts as the ultimate constraint on mission performance is now generally accepted. This has never been more true than in the low level high speed flight regime. While it is true that in a dual seat aircraft tasks can be shared and the individual work loads reduced, in a single seat aircraft, possibly operating at night or in adverse weather and in a hostile environment, the peak workload may quite easily reach unacceptably high levels. The resultant stress on the pilot will tend to make him fly higher and slower or involuntarily omit actions or make erroneous ones. Any or all of these can effect mission performance or crew survival.

The use of advanced technology in the form of multifunction electronic displays, processors, sophisticated sensors and other automated pilot aids is increasing. The need for an integrated approach to cockpit design is self-evident and considerable work is taking place both in Europe and in the United States to this end. Monochrome multifunction electronic displays have figured in this work, and indeed have now reached a high level of maturity and acceptance. Good display system design provides flight and mission data to the crew as efficiently as possible, making optimum use of the vast amount of information available in a modern aircraft and aims to avoid overloading instrument panel space or the crew information channels. But there are inevitably times when workload reaches such a pitch that tasks are voluntarily or involuntarily rejected, error rates increase, and performance is degraded to a greater or lesser extent. It is under these circumstances that the extra dimension of colour in the displays could provide an additional benefit: used correctly, colour has the potential of reducing scan times and error rates.

Monochrome cockpit displays have been very largely brought to their present reliable performance levels over the last decade. System designers and crew have learnt to live with the single colour and to use it effectively. However, few would deny that, were it available, there would be a strong subjective preference for colour. In recent years, we have seen the introduction of penetration phosphor colour displays in the tactical and command and control environment. They could even have some limited application in an exposed cockpit environment. Since then the use of multicolour shadowmask weather radar displays has become commonplace in the general aviation cockpit and, most recently, the latest generation of civil transport have adopted more advanced shadowmask displays to provide primary flight instrumentation.

It would seem that the military cockpit has been lagging in applying these new technologies: in fact, they are not truly compatible with the demanding military environment. Now, a third technology based on beam indexed colour crts, promises to meet military needs. This paper outlines the performance expected and suggests ways in which the colour capability might initially be applied.

2. TECHNOLOGY SELECTION

Any discussion of the use of colour crts should be prefaced by the consideration of application of monochrome electronic displays in the exposed military cockpit environment. Three key design tasks have included:

- achieving adequate display luminance and contrast in bright sunlit environments.

- ruggedising the relatively simple crt to enable it to withstand and maintain adequate performance under conditions of extreme vibration.
- reduction in power dissipation through raster scan technology.

These same requirements for visibility, ruggedness, and power dissipation have restricted the use of colour until now. The choice of available colour crt technologies is in practice restricted to three, see figure 1:

- penetration phosphor
- shadowmask
- beam indexing

To understand the performance achievable with these devices, it is necessary to know a little of their method of operation.

2.1 Penetration phosphor consists in principle of a dual layer of green and red phosphor on the crt screen. The electron beam is able to reach the red phosphor at relatively low energy levels,but when the anode potential is increased significantly, the beam penetrates to the green phosphor causing both red and green light to be emitted simultaneously. Although the red emission is considerably less bright than the green under such circumstances, it nevertheless causes the green to take on a more yellowish hue as it moves a little towards the red end of the spectrum. This effect can be understood with reference to the standard CIE chromaticity chart, figure 2. The low brightness of the red can in part be compensated by drawing red symbols more slowly or more frequently, effectively increasing beam current density and hence symbol luminance. Several corollaries follow:

(1) Because of the relatively lengthy tasks of switching high voltage levels, it is not practical to raster scan a penetration phosphor colour display. While this could be achieved by arranging colours field sequentially,it would result in unacceptably low brightness. In practice, penetration crts use stroke writing, enabling energy densities to be kept high but restricting considerably the type of formats that can be displayed. To increase symbol quantities in red or amber takes more time, and as a consequence, results in a brightness reduction.

(2) The use of only two phosphors implies that only colours on the red/green colour axis can be generated, figure 2. Because of desaturating effects on these colours, caused by:

- the penetration phosphor itself
- ambient illumination
- peripheral vision

at the very best, it is only possible to define three usable colours, red, amber and yellowish green, which have sufficient colour difference to be identifiable under most conditions. Clearly this is an unacceptable limitation on colour format design to the point when the returns in the form of colour coding do not match the cost/reliability penalties of greater complexity.

(3) The single penetration tube gun can be designed to be as simple and rugged as those currently used and proven in monochrome crts as can the remainder of the bulb and phosphor screen.

(4) As beam scanning speeds are restricted to maintain adequate brightness levels, display power dissipation does not usually exceed acceptable levels despite the more complex high voltage switching requirements.

2.2 By comparison, the familiar shawowmask crt technology differs considerably in terms of its design approach, figure 1, and its corresponding benefits and disadvantages.

In this case a complex triple gun allows three closely aligned electron beams to be modulated with their respective red, green and blue information simultaneously. Each beam is constrained by an aperture grill to fall on the corresponding coloured phosphor arranged in dots or stripes on the tube face:

(1) the third phosphor (blue) permits the selection of a much broader range of spectral and non spectral colours, figure 2.

(2) the aperture grill absorbs some 80 percent of beam energy, making the shadowmask approach less efficient. As a result, raster scanning, although feasible, and of course commonplace in domestic television, does not produce the brightness necessary for viewing in an exposed cockpit: again, the display must be stroke written, restricting the type of formats practically achievable.

(3) the relatively fragile aperture grill and the more complex gun inevitably introduce disturbing problems in the high vibration military environment. The sensitivity of perceived colour to such factors as beam convergence, magnetic fields etc. is also of concern.

(4) because of the energy dissipation in the aperture grill, power dissipation is high. Another related factor is that a significant amount of the beam energy is dissipated as X-radiation, a potential problem multiplied in a multi-crt cockpit configuration.

2.3 Beam indexed crts on the other hand use only a single gun which scans phosphor stripes on the tube face in a television raster. The phosphor stripes are arranged in red, green and blue triplets, the single video signal being modulated with red, green and blue information as the beam scans the appropriate phosphor. The frequency and phase of the video modulation is provided by a feedback signal derived from the faceplate itself, figure 1. As the beam scans the phosphor so an indexing signal is generated which identifies the phosphor colour that the beam is energising and causes the video to be modulated appropriately.

A number of methods have been devised to generate the index signal and it is beyond the scope of this paper to discuss their merits. Suffice it to say that beam indexing systems have been under laboratory development for more than twenty years. Such systems have not succeeded in ousting the conventional and entrenched shadowmask displays in the domestic market place. However, the peculiar demands of the military cockpit environment make the approach much more attractive, particularly in the light of recent electronic component development. Beam indexed crts have the multiple colour capability of shadowmask systems but they suffer from no aperture grill inefficiencies. As a result, brightness is appreciably higher while energy dissipation, both thermal and X-radiation is significantly less.

The relative merits of the three technologies are summarised in table 1 and a clear advantage to beam indexing is apparent. It is this colour technique which is believed to hold the best prospect for general military cockpit use and is the basis for the discussion which follows.

3. DISPLAY PERFORMANCE

The three main factors which affect the efficiency of a colour display are luminance, contrast and chromaticity (hue and saturation). The first two can be considered to govern the legibility of the display while the last indicates the information content of the colour code.

The sensitivity of the eye to colour varies across the spectrum and it is most sensitive to yellowish-green light. The sensitivity ratio of the three primaries customarily used in television, red, green, blue, is approximately 3:8:1. In other words, green appears brighter than red which is brighter than blue even though the same beam energy is energising each phosphor. These three primary colours may be combined in various proportions to give the other colours shown on the standard CIE colour chart, figure 2. Since luminance values are additive, the luminance of a colour is the sum of the luminance values of its constituent primaries. Thus the brightest colours are those with a high proportion of green and the dimmest contains only blue. By simple additive methods, the luminance of any television colour can be found if the luminance of its constituents are already known.

Note however, that the above relative sensitivities are in respect of foveal vision: peripheral vision can cause apparently arbitrary and quite striking changes to the ratio, for example blue is most effective as a colour (with most people) in the periphery.

The standard CIE colour chart gives the x, y co-ordinates of the different spectral and non-spectral colours but does not readily reflect the ability of the eye to discriminate between the different values. For this reason, an axis transformation is required which results in the Uniform Chromaticity Scale (UCS) shown in figure 3 where equal distance implies equal visual discrimination. The chart indicates which colours can easily be discriminated visually: for example, since the distance from green to orange is twice that from green to yellow, it follows that it is easier to discriminate between green and orange than it is to discriminate between green and yellow. It should be noted however, that individual phosphors are not perfectly saturated hues: to a greater or lesser extent they emit broad spectrum (white) light in addition to their dominant wavelength. This desaturation is even more apparent when one considers simultaneous energising of phosphors: for example, the addition of yellow and blue can result in completely desaturated white. This effect tends to decrease discrimination as individual colours approach each other on the diagram and can occur either deliberately when the number of colour codes are increased by mixing different combinations of the three primaries, or inadvertently when the display energises other phosphors in addition the one intended or incident sunlight is reflected from the phosphor, an efficient lambertian reflector. Of course, both these last factors can be minimised by good design, by control of the electron beam on the one hand and by the use of contrast enhancing faceplate filters on the other. Nonetheless, chromaticity differences are reduced as ambient illumination is increased, and with it, the ability of the crew to extract the information inferred by the colour code used. It is one of the reasons why redundancy coding is preferred, for example symbol shape in addition to colour.

The two factors, luminance and chromaticity can be related to yield a total colour contrast. One method of doing this is to construct a suitably scaled luminance third axis perpendicular to the figure 3 chart. The colour contrast of selected colours is then the geometric sum of their chromaticity difference and luminance contrast.

One purpose of this method is to establish whether colours can be varied slightly to

improve their egibility. Although the eye is more sensitive t chromaticity difference than luminance contrast, the most important factor when viewing the display in bright cockpit illumination conditions is total colour contrast, hence it is important to select colours which are as bright as possible while still retaining sufficient chromaticity difference.

For example, the primary blue used in domestic television is situated, for colour fidelity, in the bottom left corner of the CIE chart near the boundary of the visible spectrum. However, such colour fidelity is not a dominant factor in a cockpit display, colour contrast is. Thus the blue colour selected for a symbol can be of a longer wavelength and hence be of greater luminance, but still of comparable chromaticity difference to other selected colours.

This longer blue wavelength can be achieved by adding green to the blue video so that the colour achieved, while still within the "blue" region of figure 2, exhibits significantly greater luminance. For some symbols, particularly the smaller alpha numerics, this technique has the further advantage of producing better symbol definition on the screen. The phosphor stripe structure causes the symbol to be constructed from samples of the total symbol video. If only one of the primary phosphors is energised, sampling rates are reduced, if two, they are doubled, and if three as with white video, the integrating effect of the eye results in the symbol or scene having a comparably high resolution to a monochrome screen.

The anticipated theoretical performance of a typical beam indexed colour display has been calculated and is shown in table 2. Parameters shown are based on extrapolations on the known performance of efficient monochrome displays and assume the use of the primary colours employed in the NTSC colour television system which have CIE coordinates indicated. The unenhanced blue primary has (x, y) coordinates of (.14, .08). Note that for the reasons mentioned earlier the actual hues perceived will be desaturated by comparison with the ideal values shown in the table.

It has been established that the minimum luminance contrast ratio that can be detected is around 1:1.05 and that a ratio of 1:1.4 is easily and comfortably detected.

Similarly, it has been shown that the minimum chromaticity difference on the U" scale that is detectable is about 0.00384 and that a difference of 0.027 is easily and comfortably detected. Accordingly, these values have been used to scale the luminance contrast axis perpendicular to the UCS chart as mentioned earlier. The resultant colour contrast for a typical beam indexed display is shown in table 3. It should be noted that all the values shown for the eight colours considered are greater, many significantly greater, than the value of 0.6 established as the colour contrast level necessary to ensure comfortable detection of a symbol.

It is anticipated that more sophisticated filters than the simple neutral density one assumed in the calculations will give rise to an overall improvement in colour contrast.

The sensitivity of the eye to cockpit display brightness is temporarily reduced during the adaptation period following viewing of a bright outside world scene. It has not been possible to consider this aspect here, but work with monochrome displays has indicated that an omnidirectional autobrilliance sensor can help in this regard, increasing the display brightness with increasing outside world illumination rather than merely controlling the display brightness as a function of the ambient light incident on the screen itself.

4. USE OF COLOUR

There are many ways of conveying information visually, by pattern, size, shape, intensity, flashing and colour. Each method has different merits: for example, colour has proved extremely effective in aiding a search task. The eye will rapidly scan a complex display picking out a known target colour, rejecting other irrelevant factors. This effectiveness can be increased when colour is used redundantly with another coding dimension such as shape. However, it is quite possible to confuse the task and destroy the effectiveness of colour coding by using it indiscriminately. Available references on the use of colour to usefully convey information all agree that it should be used sparingly and with caution.

It appears that the use of colour should be systematis . ed on:

- accepted usage
- display performance
- human visual response

One is reminded that monochrome display formats can in general be devised to provide all the required information. Colour can best be used to enhance crew performance in recognising situations or in search tasks. In this way task times can be red :cd, allowing more time to be spent on critical activities that otherwise suffer omiss ons or errors in a peak workload environment.

A useful initial guide to the use of colour based on the accepted cockpit conventions is given in MIL-STD-1472B recommendations, summarised in table 4. Note that other

specifications govern the actual range of hue for these colours. In terms of redundant use of colour for warnings, table 5 compares the use of colour with the conventions used on some current monochrome displays. Not only does the redundant use of colour serve to accentuate information, if the hue is lost for some reason, the information content will still be available to the crew by interpretation of symbol shape, flashing etc. Loss of colour might occur for example when:

- the display is viewed peripherally - all colours being seen as white.
- display performance/ambient conditions are such as to cause sufficient hue desaturation that the eye cannot easily discern colour differences.
- the display fails with the indexing circuit open loop resulting in a monochrome display.
- deliberate manual crew intervention to select a monochrome display, e.g. red to preserve night vision.

Another example of the use of colour is in the conventional ADI where blue represents pitch angles above the horizontal, a very clear indication of the direction of "up". Although blue is less effective for small symbols, the larger area provided by the "sky" colour is most demanding and effective a long way in to the periphery.

Uses for some 5 colours have been identified in this discussion so far, red, yellow, green, blue and white. A number of authorities recommend the use of only 3 to 5 hues, suggesting that more will only tend to confuse a viewer. While this opinion should be accepted, it is recommended that any display should be basically capable of generating more colours to ensure good colour contrast and to permit growth to more complex use of colour in some formats should this prove desirable in the future. It is notable that quite an extensive range of colours is planned for use in the civil transport electronic flight instruments currently under development.

The use of white deserves special mention, it provides the best resolution and it can be achieved by applying video to the crt unmodulated by the indexing signal in either raster scan or stroke writing modes. It provides the greatest peak brightness at a reasonable contrast level. As such it should probably be used to display imaging sensor information, any symbol overlays being achieved in one of the other colours. However, it should be noted that this use of white will not result in the same high level of contrast and number of grey shades achieved with current monochrome displays unless a striking increase is made in contrast enhancement filter efficiency or the display is used in such a way that ambient light is not incident directly on it.

A further factor to consider is the likely use of multiple displays in the cockpit. It is important that they are used consistently, particularly with regard to:

- hue
- saturation
- luminance
- use of colour

Such needs may tend to drive the cockpit designer towards the use of a well specified and standardised display technology, if not to actual standard displays.

The scale of the integration and task and range of standardisation required is indicated in part by figure 4 which suggests some of the many different format categories that would be required to be considered.

5. CONCLUSION

Current studies suggest that beam indexed displays are likely to be available for airborne use in the early 1980s. It is notable that studies in the use of colour carried out to date cannot have been completely representative as suitable high performance hardware has not been available for use under operational conditions.

The potential for crew performance enhancement offered by beam indexed colour displays suggests that their cost-effectiveness should be evaluated for the next generation fighters likely to be used extensively in the demanding high work-load environment created by low level high speed flight.

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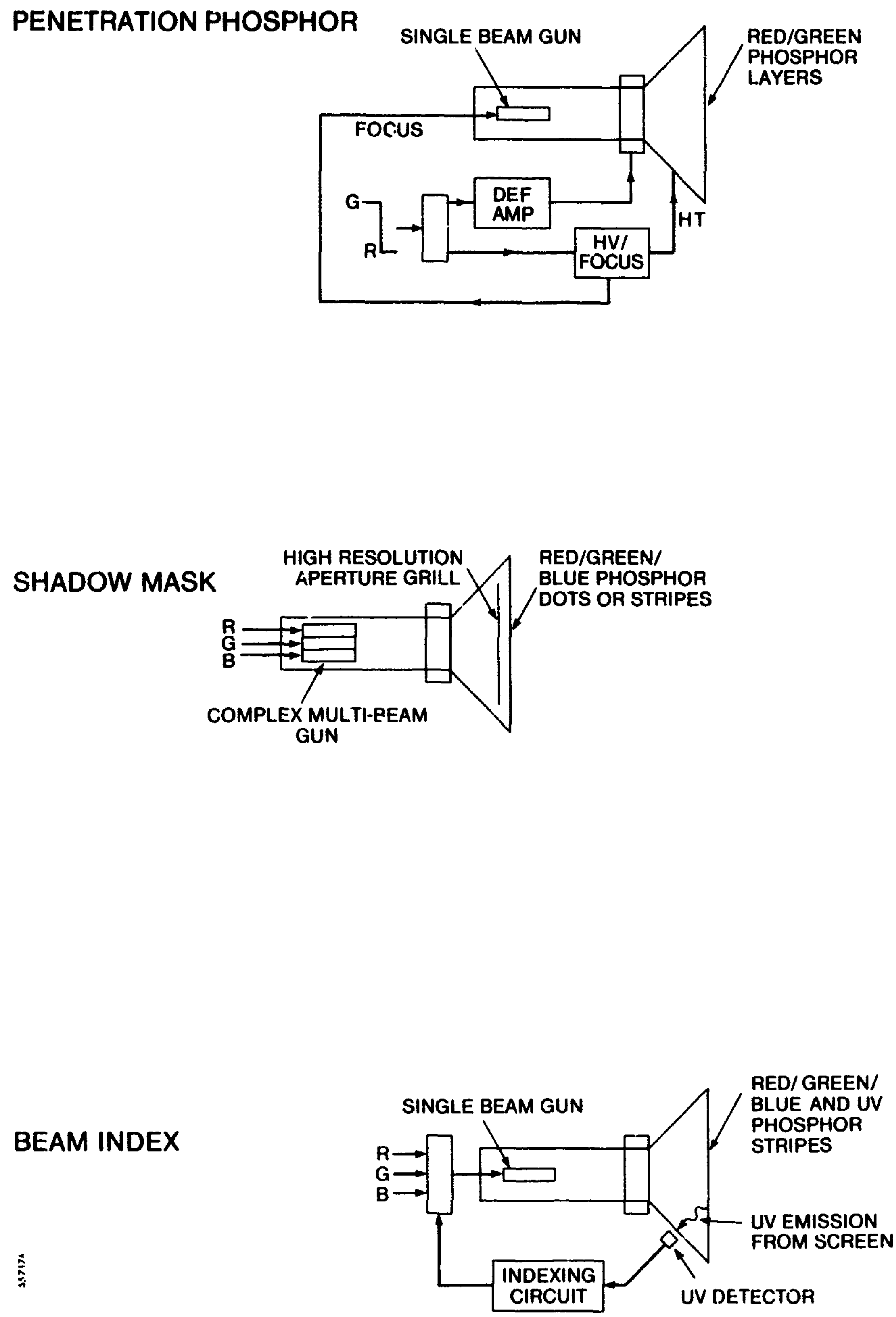

Figure 1 Technology Choice

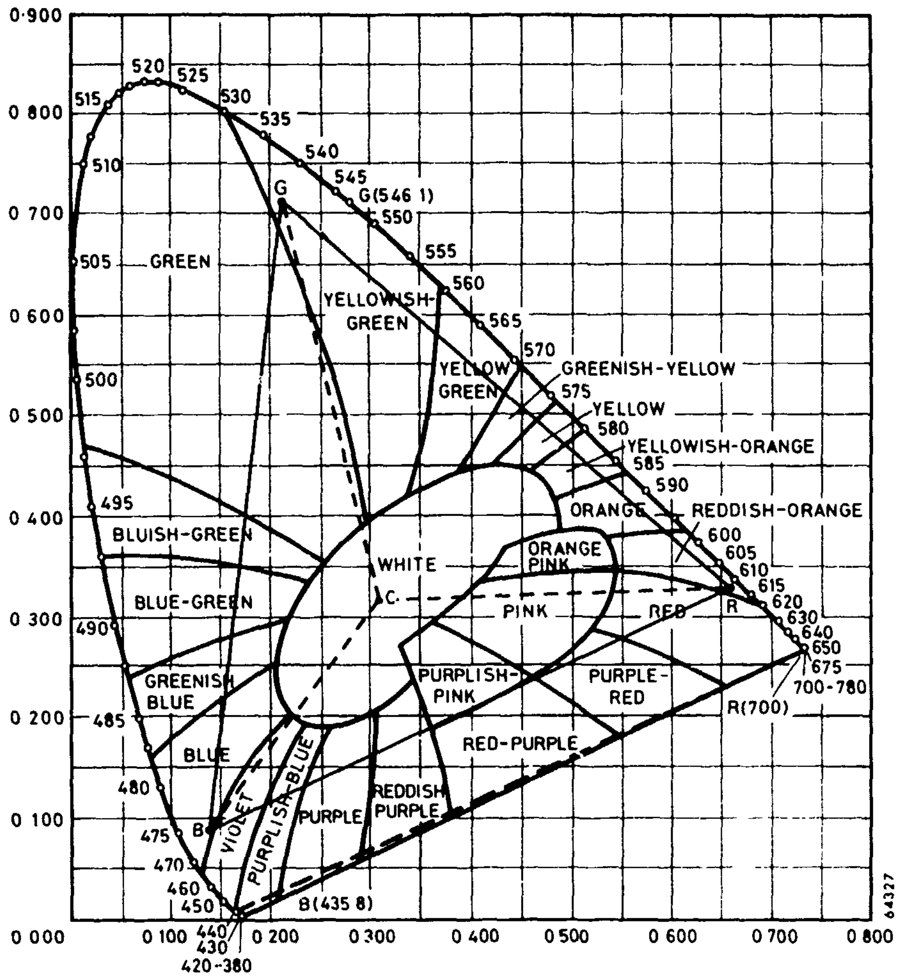

Figure 2 Standard CIE Chromaticity Chart

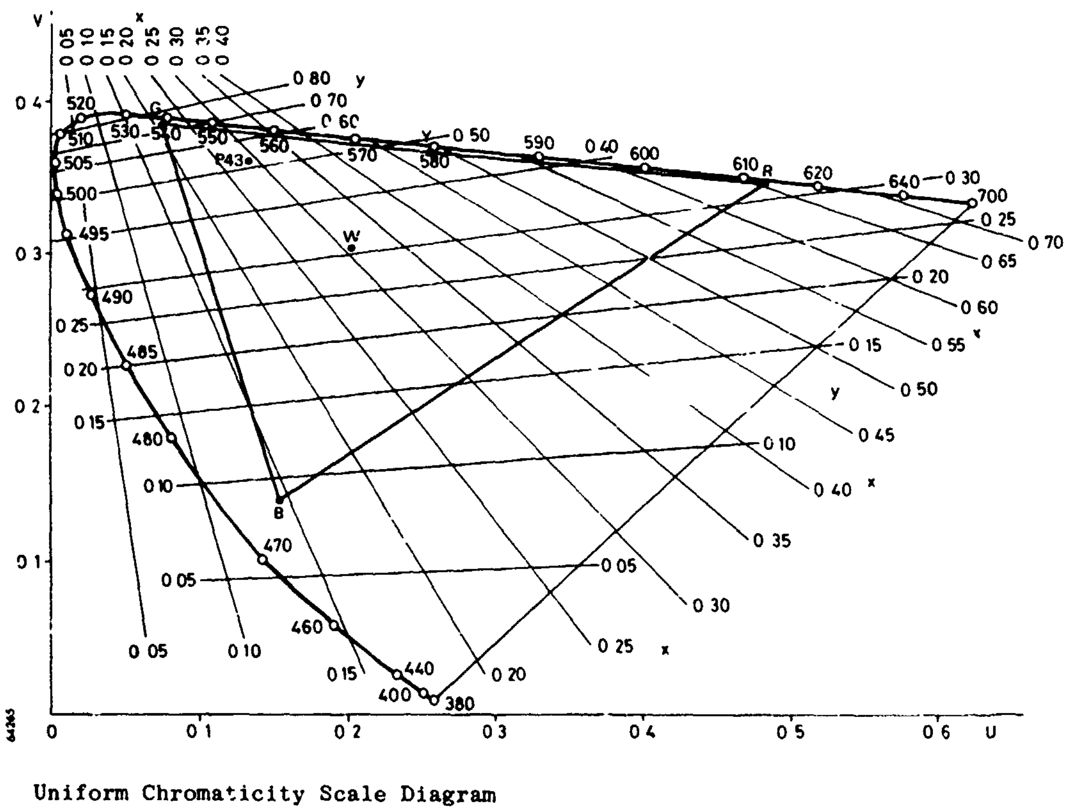

Figure 3 Uniform Chromaticity Scale Diagram

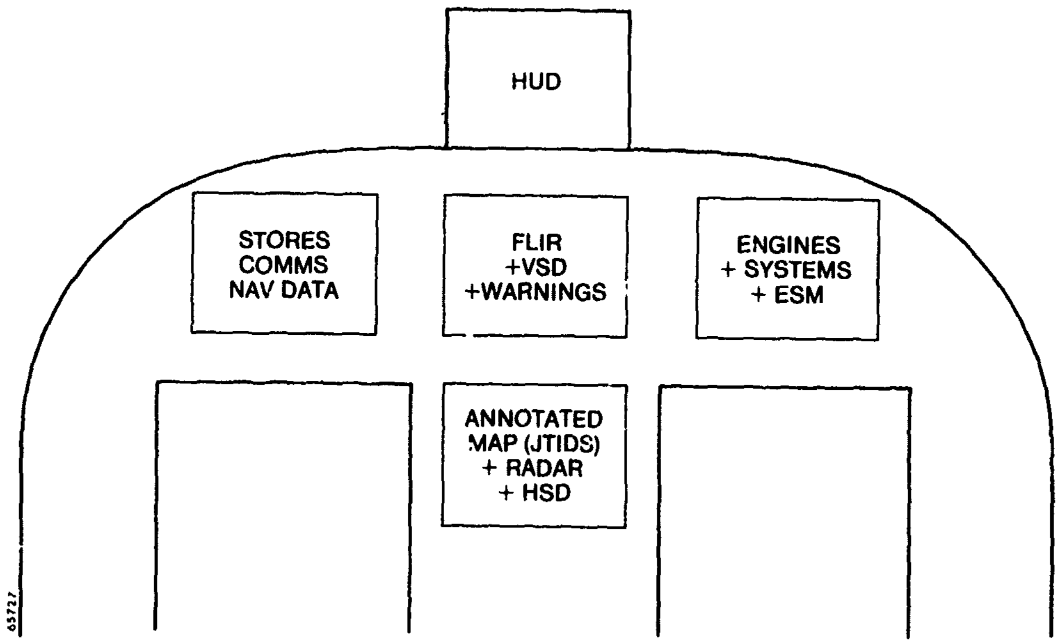

Figure 4 Multiple Display Consistency

	PENETRATION PHOSPHOR	SHADOW MASK	BEAM INDEX
PRIMARY PHOSPHOR	2	3	3
USABLE COLOURS	3	8	8
RASTER SCAN FEASIBLE	NO	NO	YES
ADEQUATE CONTRAST	NO	MARGINAL	YES
RUGGEDNESS	YES	NO	YES
POWER DISSIPATION	ACCEPTABLE	HIGH	ACCEPTABLE
X RADIATION	ACCEPTABLE	HIGH	ACCEPTABLE

Table 1 Colour Display Techniques

	LUMINANCE OF PRIMARY CONSTITUENTS			PEAK LUMINANCE BEFORE FILTER	CIE CO-ORDINATES			
DISPLAY COLOUR	RED	GREEN	BLUE	Ft. L	X,	Y	U,	V
RED	250	–	–	250	.67	.33	.48	.35
GREEN	–	500	–	500	.21	.71	.08	.38
CYAN	–	200	80	280	.16	.22	.12	.25
WHITE	250	500	80	830	.31	.32	.20	.31
PURPLE	97	–	80	177	.26	.13	.26	.19
MAGENTA	250	–	55	305	.43	.21	.37	.27
ORANGE	250	170	–	420	.57	.42	.33	.37
YELLOW	250	390	–	640	.48	.48	.25	.37

65719A

Table 2 Display Colour Characteristics

SYMBOL	OBSERVED PEAK LUMINANCE Ft LAMBERTS (10% Neutral Density Filter)	SYMBOL COLOUR CONTRAST AGAINST DIFFERENT BACKGROUND COLOURS IN AN AMBIENT ILLUMINATION OF 10^5 LUX								
		RED	GREEN	CYAN	WHITE	PURPLE	MAGENTA	ORANGE	YELLOW	BLACK
RED	25	0	1.52	1.46	0.95	1.26	0.82	0.69	0.85	1.26
GREEN	50		0	1.25	0.91	1.63	1.64	1.32	1.00	1.36
CYAN	26			0	0.71	0.96	1.20	1.28	1.15	1.11
WHITE	83				0	1.36	1.27	1.12	0.94	1.46
PURPLE	17.5					0	0.85	1.14	1.18	1.11
MAGENTA	30.5						0	0.88	1.00	1.22
ORANGE	42							0	0.68	1.24
YELLOW	64								0	1.38

Table 3 Theoretical Colour Contrast

(MIL STD 1472B RECOMMENDATIONS)

COLOUR	STATE	RESULT
Flashing Red	Emergency	Immediate operator action
Red	Alert	Corrective/ override action must be taken
Yellow	Advise	Caution; recheck is necessary
Green	Proceed	Condition satisfactory
White	Transitory Function	No "right" or "wrong" indication
Blue	Advisory	Should be avoided

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Table 4 Accepted Usage

CONDITION	MONOCHROME	COLOUR
Emergency Alert	Flashing Area	Flashing Red Area
Caution	Contrast Inverted Area	Yellow Contrast Invertion
Normal Operation	Positive Contrast Symbol	Green or White Positive Contrast

Table 5 Redundancy

HELMET-MOUNTED DEVICES IN LOW-FLYING HIGH-SPEED AIRCRAFT

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SUMMARY

There is considerable interest in the use of helmet-mounted devices worn by pilots of military aircraft whilst flying at high speed and low level. It has been anticipated that the buffeting vibration associated with this flight regime could affect the use and design requirements of helmet-mounted devices, and this paper reports the results from two relevant simulation experiments. The first assessed the amount of movement occurring between the pilot's helmet and his eyes, whilst the second concerned the legibility of information presented on an experimental LED matrix display.

It was concluded that aircraft vibration did not cause significant helmet movement, in comparison with natural voluntary head motion, and that the degrading effect of aircraft vibration on the legibility of displayed information could be counteracted using a brighter display.

1 INTRODUCTION

During low-level high-speed flight in military aircraft the turbulence encountered can subject the pilot to violent body vibrations. It is of considerable interest to the designers and users of helmet-mounted sights and displays to know what consequences these irregular forces have on the design requirements of helmet-mounted devices.

This paper describes two separate simulation studies, the first concerned with measurements of the movement of the pilot's flying helmet relative to his eyes, whilst the second is an assessment of the legibility of information projected from a novel form of helmet-mounted display, in which the image is derived from a matrix of light-emitting diodes.

2 MOVEMENT OF A PILOT'S HELMET DURING SIMULATED LOW-LEVEL HIGH-SPEED FLIGHT

All the present forms of helmet-mounted sight or display incorporate an image source together with a means of collecting and redirecting the emitted light so that it enters one of the pilot's eyes, enabling him to see a clear bright virtual image superimposed upon the normal scene. These electronic and optical components are attached to the helmet, so that displacement of the helmet relative to the pilot's display-viewing eye can move his eye beyond the exit pupil of the optics. Although it is known[1] that the inertial forces arising during turning manoeuvres can cause considerable helmet movement relative to the pilot's eyes, little was known about the magnitude of helmet displacements resulting from aircraft buffet vibration. This experiment was conducted primarily to assess the latter, but it was also of interest to compare the movement of the current RAF Mk 3B helmet with that of the USAF HGU 22/P helmet, and to assess the effect of attaching a helmet-mounted display device to the latter.

2.1 Experimental method

2.1.1 The displacement measuring system

The essential requirement for this experiment was a means of measuring the displacement of the helmet shell relative to the wearer's right eye, arranged so that this measurement system neither altered the helmet weight significantly nor perturbed its movement.

The device developed fulfilled these requirements satisfactorily, and produced separate electronic signals, corresponding to vertical (Z) and horizontal (Y) displacements, which were reasonably linear within 5 mm of the centre. The basis of the system was a position-sensitive photodiode attached to the helmet, arranged to receive the image of a small lamp mounted on an extension from a bite-bar held between the subject's teeth. The lamp filament was thus attached rigidly to the skull and could be positioned 12 mm in front of the subject's right eye. The optical arrangement, illustrated in Fig 1 was such that any paraxial movement of the filament relative to the lens and photodiode moved the image of the filament across the photodiode surface, and hence produced stable signals. The photodiode and lens assembly was mounted on the helmet shell using alloy brackets, as illustrated in Fig 2. For the Mk 3B helmet this necessitated removal of the vizor, but the bracket for the USAF helmet was made as an extension of the oxygen-mask fixing plate. The oxygen-mask was itself modified to allow the bite-bar to protrude forward by removing the microphone and an annulus of rubber.

2.1.2 The helmets

Although only two types of helmet were considered, the USAF helmet could be used both with and without a helmet-mounted display and also with an alternative set of

'universal' liners replacing the standard items. This resulted in five helmet conditions which were as follows:

Helmet condition A - in which the USAF helmet was fitted with artificial foam 'universal' liners, which provided a tight fit by virtue of the time-dependent resilience of the foam. The helmet had also been modified to accept a Hughes Aircraft Co helmet-mounted display with a position-sensing system, and RAF type oxygen-mask and earphones.

Helmet condition B. This was the same as the first, with the addition of a replica CRT display to the right side of the helmet.

Helmet condition C. In this condition the USAF helmet was used with the standard 'form-fit' liners, tailored to suit the individual pilot. This technique for producing a bespoke helmet made use of a rigid plastic foam moulding of the space between the wearer's head and the helmet shell, although the moulding inner surface was rendered more compliant and comfortable by a thin soft plastic foam layer covered with leather. Modifications to the shell and incorporation of the display coupling were as for the first condition. The bespoke liners had received about six months of intermittent flight use.

Helmet condition D. This was the same as condition C but with the addition of the replica CRT display.

Helmet condition E - which was the RAF Mk 3B helmet, differing from the USAF helmet in both the design of the shell and the form of the suspension. The latter was made from nylon webbing, attached to the shell and sewn to form a cradle covering the wearer's crown, so that contact between the shell and the skull was prevented by tensioning the webbing. The position and fit of the helmet could be adjusted by drawstrings acting on the webbing, with additional stability resulting from tension applied to a nape strap and the ear-cups. These helmets were fitted to the subjects using normal operational criteria for tightness and comfort.

2.1.3 The subjects

The two RAF test pilots who acted as subjects for this experiment were chosen because they had been fitted with the individually tailored liners for the USAF helmets. The first subject was near average but the second was considerably larger, in both stature and head size, in comparison with RAF aircrew.

2.1.4 Simulation of aircraft motion

Simulated aircraft motion was produced using the RAE two-axis man-carrying rig, arranged to reproduce accelerations in heave and sway recorded from both a Canberra and a Phantom, flown at 250 feet and 350 knots.

The frequency response of the rig was reasonably constant between 0.5 hertz and 25 hertz, and the rms acceleration levels were about 0.25 g in heave and 0.1 g in sway for both aircraft. The characteristics of the Canberra were considered to be realistically reproduced, but those from the Phantom seemed less authentic, perhaps because of the absence of significant high frequency components.

The subjects sat in a Canberra type ejection seat and used harness tensions appropriate to the simulated flight regime.

2.2 Experimental procedure

In addition to using the five helmet conditions, two aircraft motions and the two subjects, each subject was asked to produce two types of head motion. In the first case the subject was asked to look straight ahead as though aiming the helmet, and in the second he was asked to move his head as though searching for other aircraft and ground targets during flight. During both these head motion conditions the subject underwent the simulated aircraft vibration.

Both subjects wore the different helmets, the USAF both with and without the replica display and with both types of liner, experienced the Canberra and the Phantom vibration, and produced minimal or searching head motions, in a random sequence of combinations. Signals from the helmet displacement measuring system were recorded on a fm tape-recorder, and analysed subsequently using a Hewlett-Packard signal analyser.

2.3 Results

The measurements can best be shown as the locus of the lamp filament with respect to the lens and photodiode, which is equivalent to the right eye displacement relative to the helmet shell. Two such loci, recorded over 2 minute periods, are shown in Fig 3a&b, where the second subject, wearing the USAF helmet with tailored liners, experienced the Phantom vibration. In Fig 3a, whilst maintaining a fixed forward direction of regard the displacement had a range of less than 3 mm, but when the subject produced head movements appropriate to searching, as in Fig 3b, the displacement increased considerably, covering a range of about 12 mm.

An analysis of variance of the results revealed that the only significant factors were this substantial effect due to voluntary head motion, and a difference between the

displacements due to the different manner in which the subjects carried out their simulated searching. It was also apparent that the vertical displacement exceeded the horizontal when subjects minimised their involuntary head motion, but that horizontal displacements dominated during the simulated searching trials. Table 1 summarises the results as the average rms displacements, in both the horizontal and vertical directions, for the significant variables. The average ranges of helmet displacements were approximately four times these rms values.

2.4 Comments

Although the statistical basis of this experiment was poor, since only two subjects were used, it was reasonably evident that the magnitude of helmet movement during simulated low-level high-speed flight was in the order of a few millimetres when the wearer attempted to minimise his head movements. In contrast, comparatively large displacements occurred due to natural head motion, and any effects arising from differences between helmet types, their form of suspension, the addition of a display, or the variety of aircraft vibration were significantly less marked.

It is suggested that helmet displacement on the wearer's head results mainly from angular acceleration of the head and the rotational compliance of the human scalp. Consequently all well-fitting helmets would suffer some displacement under vibration, irrespective of their detailed design.

3 LEGIBILITY OF A HELMET-MOUNTED MATRIX DISPLAY DURING SIMULATED LOW-LEVEL HIGH-SPEED FLIGHT

3.1 The matrix display

The Flight Automation Research Laboratory of Marconi Avionics has devised a simple helmet-mounted display in which the image was derived from a miniature matrix of light-emitting diodes (LEDs). An early experimental version of this display consisted of the LED matrix, and its subsidiary circuit boards and optics, mounted on a skeletal head-band, as illustrated in Fig 4. The projected image was seen by the user to be in his normal forward direction of regard, to be red in colour and have an angular extent of about 10 degrees. The format is illustrated in Fig 5, and includes some fixed characters below the 20 by 23 element matrix.

The LED matrix was operated by switching an energising current to a chosen element, which emitted light when energised. Although only one element could therefore emit at any instant, a format could be displayed by energising the necessary elements in sequence and, providing the cyclic rate was sufficient, no flickering or discontinuity was normally apparent. The repetitive sequence of element address codes was sent from a computer to the head-mounted electronics as a BCD pulse train along a single cable and, since each address code took 250 μs to transmit, a set of characters made up from 40 elements could be repeated 100 times per second.

The optical projection system consisted of a glass prism, which collected the light from the downward-facing matrix, and a spherical section combiner, which reflected the light into the user's right eye. In this experimental version of the display the combiner glass was inserted into the vizor attached to the brow of the head-band. In use, the device gave an unrestricted view to the left eye, but the right eye looked through an area of confusion, produced by the circular joint between the combiner and the vizor. The right eye's view was also tinted blue because the combiner was coated with a dichroic layer having a high reflectivity for the red image-forming light.

3.2 Object of the simulation

It had been anticipated that some difficulty in perceiving the display image could arise due to a combination of high background light level and the irregular body vibration due to high-speed low-level flight. In order to assess the legibility of the display under these conditions, two experimental measurements were made, the first being an assessment of the detectability of an individual LED element, and the second an examination of the errors arising from the display of numerical symbols.

3.3 Experimental method

3.3.1 Apparatus

The RAE man-carrying two-axis vibration rig was used to reproduce the characteristic motion of a Canberra aircraft flown at 250 feet and 350 knots. Mounted on the rig platform was a seat from a Sea King helicopter, in which the subject was secured. An artificial bright sky was produced by supporting a 2 metre diameter fibre-glass resin hemispherical dome above the rig. Four halogen flood-lights attached to the rim of the hemisphere were positioned so that the whole inner diffusing surface was reasonably evenly illuminated. This whole experimental arrangement is illustrated in Fig 6, where the hemisphere was tilted forward so that the subject had the sensation of flying in sunlit cloud and was required to view the projected display against such a bright background.

The experimental helmet-mounted matrix display was fitted to the subject so that his right eye occupied the centre of the optical exit pupil. The display was controlled in both brightness and content by a PDP-11 computer, programmed to produce the visual

stimulae, receive the response, carry out timing operations and collate the accumulated data. For the first task the subject made responses by pressing a hand-held push-button but in the second the response was timed by a signal obtained from a throat-microphone worn by the subject, whilst the correctness of the response was monitored by the experimenter who signalled the errors using a keyboard.

3.3.2 The tasks

The first task assessed the subject's ability to detect the presence of a single illuminated element in the display under two conditions of ambient brightness and three levels of vibration. The brightness of the artificial sky forming the background to the displayed image was set at either 680 nits or 5100 nits, and the rig was arranged to produce vibrations of either the full Canberra level or half this level, or no vibrations. In all combinations of these conditions the subject was given sufficient time to adapt to his circumstances and become familiar with the task. For this detection experiment the image was seen as a small (6.5 minute of arc) red square superimposed on the brighter background, each presentation lasting 3 seconds with an interstimulus interval varying randomly between 1 and 3 seconds. The brightness of the element was controlled to have one of ten levels, spanning a range between 3.4 nits and 340 nits, and each level was presented ten times in a random sequence, necessitating 100 presentations per trial condition per subject. Six male scientists having 6/6 unaided vision were used as subjects.

For the second experiment the task involved reading a single displayed digit, which was made up from a dot-matrix of 5 by 7 elements in accordance with the symbol designs proposed by Huddleston[2], and the subject was required to call out the number as soon as he recognised it. All three levels of vibration were used, but the ambient brightness was fixed at the higher level of 5100 nits. Four presentation durations (0.1, 0.3, 0.5 and 5.0 second) and four levels of display brightness (116, 132, 292 and 1160 nits) were introduced, but the two subjects did not receive all combinations of these levels. The short duration and comparatively low display brightness levels were found to be necessary to make the task of reading such comparatively large (60 × 75 minutes of arc) characters more difficult.

3.3.3 Results

Although there was considerable variation between subjects the results of the detection experiment have been summarised as graphs relating the average probability of detecting the single element, and the average response time for such detected stimuli, to the display brightness. Figs 7 and 8 show the results in this form, for the three levels of vibration and two levels of brightness employed. The general effect of the simulated aircraft motion was to decrease the likelihood of detecting a 'signal' and increase the response time.

The results of the second experiment are shown in Table 2 as the probability of successfully recognising a single digit, displayed at certain combinations of brightness and duration, for the three vibration levels. Again, the general effect of the simulated aircraft motion was to increase the chance of perceptual error.

3.4 Comments

The measurements of the variation of detection probability with display brightness show a series of S-shaped curves characteristic of a complex stochastic threshold phenomenon. The conventional definition of a 'detection threshold' is the stimulus brightness at which half the stimuli are detected on average over all subjects; using this criterion the effect of vibration was to lift the 'stationary' threshold by 45% at half power and by 60% at full power for the lower (680 nits) ambient light level. In the brighter surroundings (5100 nits) this effect was more marked, with the threshold rising by 130% and 200%, for half and full power Canberra motion respectively, which indicates an exaggerated effect when high ambient brightness and high levels of whole-body vibrations are combined.

Although the threshold brightness levels for stationary subjects were low (~2%) in comparison with the ambient light levels, the response time data suggested that, at these thresholds, the average time taken was considerably longer than for brighter displays. Indeed, the average response times for detected stimuli fell to an apparent asymptotic value of about 0.35 second, for only those higher levels of display brightness at which no stimuli passed unnoticed. This effect seems to be constant for all combinations of ambient brightness and vibration levels. This indicates that a more realistic criterion for assessing the effect of brightness and vibration conditions on detection of a stimulus would be to assess the brightness at which all signals could be seen with minimum delay. Using this criterion the effect of vibration, at the lower ambient brightness level, was to increase the 'comfortable' brightness level from about 34 nits to about 70 nits and 160 nits, for the half and full power motion respectively. These are changes of about 100% and 460%, and are significantly more marked than the corresponding changes of the '50% detection' threshold. Unfortunately the limiting display brightness did not allow this effect to be assessed in sufficient detail at the higher background light level.

The paucity of data from the digit legibility measurements does not allow hard quantitative conclusions. When the subjects were still they could read the displayed numbers with very few errors, even when displayed at low brightness and present for only 0.1 second. When subjected to vibration their performance fell and was only restored by

increasing both the display brightness and stimulus duration appreciably. It is likely that an increase in the minimum display brightness from about 4% to about 30%, of the ambient level, would be necessary for adequate legibility in conditions of high external light levels and the vibration produced by low-level high-speed flight, a conclusion which reinforces that from the first detection experiment.

4 CONCLUSIONS

Bearing in mind the small number of subjects used in these experiments, it is reasonable to conclude that the buffeting vibrations associated with low-level high-speed flight had a small effect on the movement of a pilot's helmet, relative to his eyes, in comparison with the helmet movement due to natural head motion. However, aircraft vibration degraded the legibility of information displayed on a novel form of helmet-mounted LED matrix display, but increasing the display brightness could counteract this loss.

Table 1

THE RMS DISPLACEMENTS (IN MILLIMETRES) AVERAGED OVER ALL HELMET CONDITIONS AND BOTH CANBERRA AND PHANTOM VIBRATIONS

Subject No.1		Subject No.2		
Head still	Head moving	head still	Head moving	
0.26	0.68	0.40	1.58	Vertical
0.18	0.96	0.20	1.86	Horizontal

Table 2

SUCCESS PROBABILITY (%) WHEN READING A SINGLE DIGIT DISPLAYED ON THE MARCONI AVIONICS LED MATRIX DISPLAY

Presentation time (seconds)	No vibration				½ level vibration				Full vibration			
	116	132	292	1160	116	132	296	1160	116	132	296	1160
5.0		100					100	100		97	98	100
0.5		98			97				84	65		
0.3			100		94		99	100	65		89	99
0.1	95				74				39			

Display brightness (nits)

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No.	Author	Title, etc
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2	H.F. Huddleston A.H. Adams B.M. Robson	A comparison of two computer-generated alpha-numeric fonts. RAE Technical Report 71071 (1971)

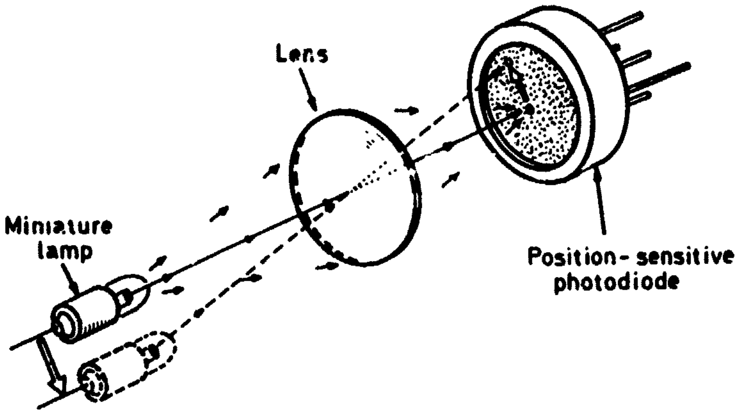


Fig 1 The optics of the displacement measuring system

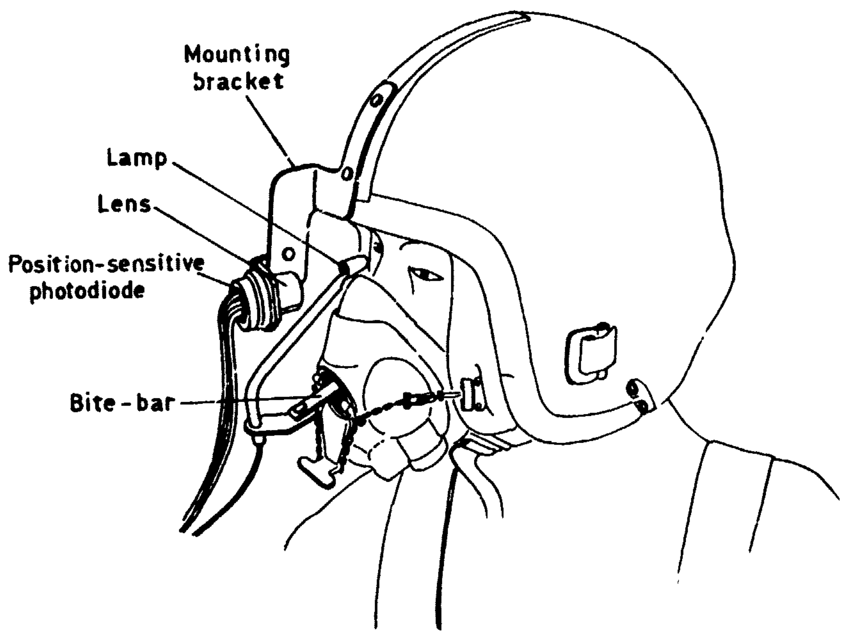
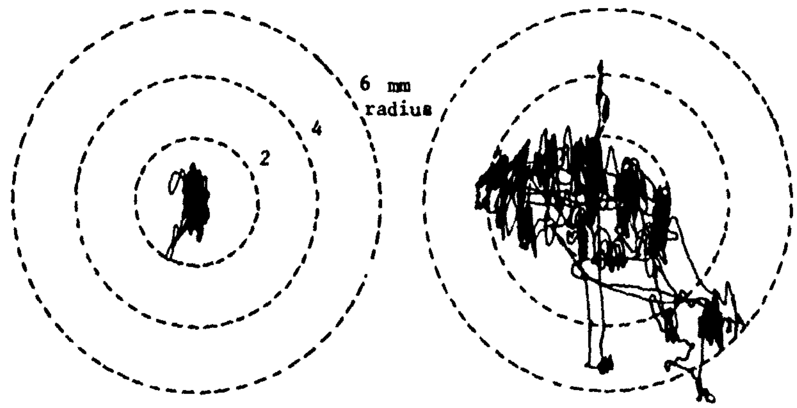


Fig 2 Illustration of the displacement measuring system on the RAF Mk 3B helmet



a Subject looking straight ahead

b Subject carrying out a simulated search task

Fig 3 The loci of displacement for subject No.2, wearing the USAF helmet fitted with tailored liners whilst undergoing Phantom vibration

Fig 4 The Marconi Avionics LED matrix display mounted on a head-band

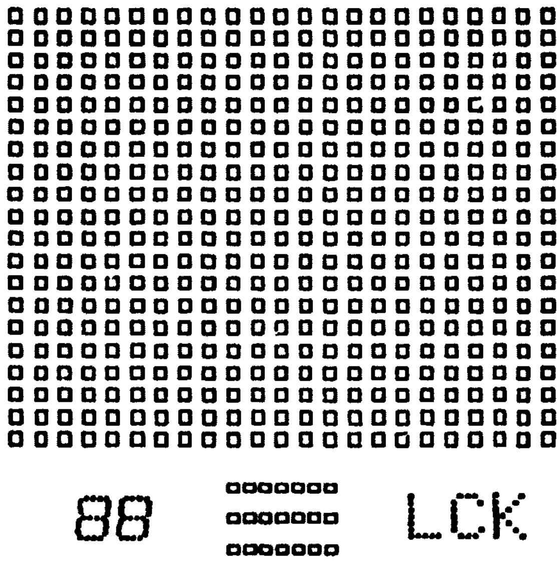


Fig 5 The LED matrix format

Fig 6 The vibration rig and artificial bright sky

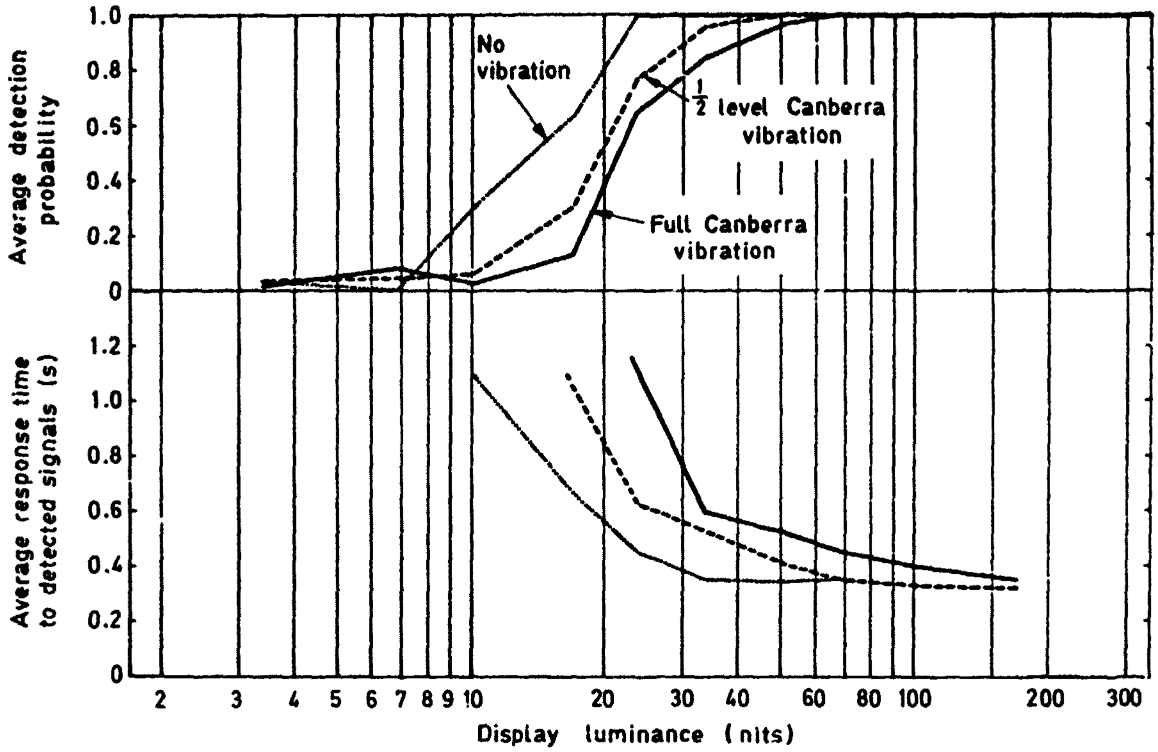


Fig 7 Detection probability and response times for viewing a single element against a background brightness of 680 nits

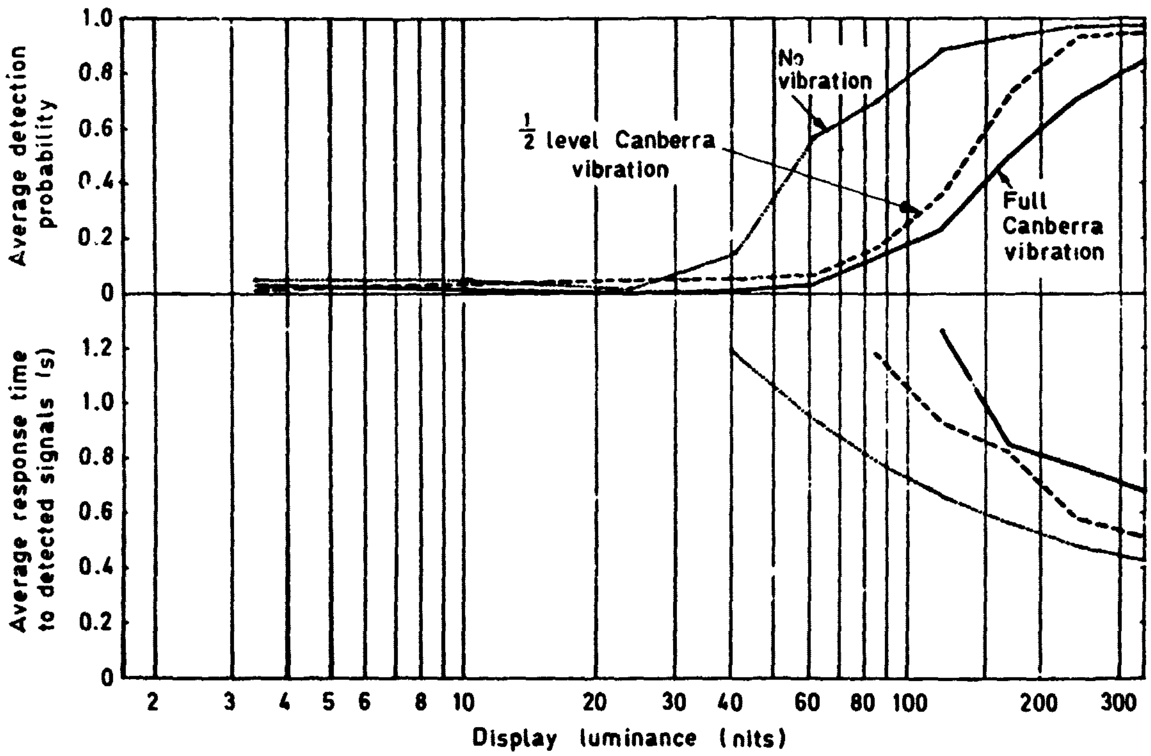


Fig 8 Detection probability and response times for viewing a single element against a background brightness of 5100 nits

THE ROLE OF HELMET MOUNTED DISPLAYS IN HIGH-SPEED LOW-LEVEL FLIGHT

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SUMMARY

During critical phases of flight operations, the requirement for shifts of gaze between the environment outside the cockpit and the interior of the cockpit is a problem which can be eased by the development of an effective helmet mounted display capable of presenting sensor and aircraft position and condition information. In both fixed wing and rotary wing aircraft, a "head-out-of-the-cockpit" attitude is considered to be highly desirable. An effective helmet mounted display is one which is comfortable to use, does not degrade normal visual functioning, can present the required information and does not increase crew fatigue due to weight and bulk. The general design concerns regarding helmet mounted displays apply to those to be used in a high-speed low-level environment. Some of the design parameters take on special significance, however, in high-speed low-level flight.

INTRODUCTION - Advances in technology made possible the development of virtual image displays over two decades ago. The Head-Up Display, or HUD, was the first virtual image display to become operational. The HUD which is an aircraft mounted device has proven very useful in aircraft operations. Shortly after the HUD was developed, efforts to develop a helmet mounted display were initiated. Since the HUD was aircraft mounted, the information which would be presented by means of the HUD was only available when the pilot looked straight ahead, which is where the HUD is located. In addition, the field of view of the HUD was small, perhaps twelve degrees. There are many situations in which it would be decidedly advantageous for a pilot, and perhaps other aircrew members as well, to have certain information available without looking into the cockpit at an instrument panel or even at a fixed HUD. This is the so-called "head-out-of-the-cockpit" attitude. One situation in which such an attitude is desirable is in high-speed low-level flight. One method of accomplishing that desired end is by use of a helmet mounted display. A helmet mounted device, whether display or sight, must as a minimum, consist of a device to generate the information to be displayed, an optical system to transfer the image from the display generator to the eyepoint and some means of determining where the pilot is looking - a head/eye position sensing scheme. Numerous mechanisms for providing these various elements have been proposed. The proposals will not be reviewed here, rather this discussion will examine some of the factors which must be considered in selecting and integrating the elements of the display with particular reference to the high-speed low-level flight regime.

The goal of a helmet mounted display design should be to provide a display which will permit cockpit personnel to simultaneously obtain the information required about both the aircraft and the environment outside the aircraft accurately and comfortably. The general considerations regarding the design of head coupled displays have been discussed elsewhere (1). The high-speed low-level flight environment presents special problems which must be evaluated.

If the aircraft is a fixed wing aircraft, the low-level phases of the flight may be conducted at altitudes of thirty to sixty meters over land and skimming wave tops over water in both attack and fighter type aircraft at subsonic speeds (2). In the attack aircraft, the crew will be required to navigate using both speed-time-direction information and terrain or environmental checkpoints. In both types of aircraft, sensor information regarding both terrain features and threat detection is required. In helicopter low-level operations, the altitude over land can be in the units rather than tens of meters, and while the speeds may be only one tenth that of the attack or fighter type aircraft, they are still significant relative to the altitudes - forty to seventy knots (3). In both cases it is extremely important that a pilot detect obstructions at as great a distance as possible. It is also important that sensor information be provided in a timely manner, and that other vital information regarding aircraft status and navigation be available.

TERRAIN INFORMATION - Terrain information is required for two types of operations - terrain avoidance and terrain following. The aerodynamic qualities of the aircraft will, of course determine the limits within which each of these operations can be performed. Within these limits, the information supplied to the aircrew will significantly affect the level of performance. One study of the extent to which sensor information can affect performance in low-level operations at night used performance of the low-level operations in daylight as a baseline against which to evaluate the night performance. The results indicated that performance at night was as good as the baseline performance or poorer, depending on the specific sensor-display combination being used (3). When that sensor information was displayed via a helmet mounted display, the results were negative, that is, the maneuvers could not be performed, unless a boresight reference marker was provided on the display. The assumption is that the night condition, plus the mock-up cockpit from which the operations were conducted in the test helicopter, produced reference conditions which were impoverished artificially, and that a single reference marker was adequate to orient the pilot. With the marker in place, the required maneuvers could be adequately performed.

For both terrain avoidance and terrain following information, sensors such as radar altimeters or others which can provide anticipatory terrain information such as altitude of obstructions, either man

made or natural, or computer generated navigation information which can anticipate rises or sharp drops of the terrain can be provided via a helmet mounted display to aid flight crews in accomplishing a high-speed low-level maneuver.

THREAT DETECTION - Threat information can be displayed by means of a helmet mounted display during a maneuver which requires a "head-out-of-the-cockpit" attitude. Sensors which detect radar, lasers or anti-aircraft missiles can provide warning information to aircrews so that threat avoidance or neutralization procedures can be initiated. If an aircraft has been detected by ground based radar, avoidance maneuvers including lower level operations can be accomplished. If the detecting sensor indicates an airborne threat, tactics which have been developed to avoid or neutralize the threat can be employed, again using helmet mounted display information to both diagnose and respond to the threat.

AIRCRAFT INFORMATION - The minimum aircraft condition information required to conduct the high-speed low-level operation is probably aircraft attitude and speed. These data need not be continuously available, but should be available on demand. A pilot may call for the desired information by activating a call mechanism. Since these are important for high-speed low-level operations, the call mechanism for them should ideally be located on the aircraft controls. Other information may be called for from other locations, but the critical information should be available at the finger tips.

HELMET MOUNTED DISPLAY DESIGN CONSIDERATIONS - The helmet mounted display design decisions which are most specifically related to the high-speed low-level operational regime are those related to the selection of the style of the information to be displayed, acuity requirements of the information, the brightness of the display, and the effect of the display scheme on the visual responses which might degrade rather than enhance overall performance.

The style of the presentation requires decisions regarding alpha-numeric information and symbology. Some types of information are most readily comprehended in numerical form while others are most readily comprehended in symbolic form. Aircraft condition information which is normally displayed via instruments such as altitude and airspeed should probably be displayed numerically via a helmet mounted display. Aircraft condition information such as attitude should be displayed symbolically. Anticipatory terrain avoidance/following information should probably be displayed numerically. Terrain avoidance altitude information should be continuously available while mean sea level altitude should be available on demand.

The acuity requirements of the displayed information would, at first glance, seem to be simple - large, easily readable numbers and symbols. Large stimuli may not be readily useable on a helmet mounted display. An examination of the situation suggests that the visual angle subtended by numbers and symbols presented on a helmet mounted display should be only slightly larger than, or equal to, that subtended by comparable information at the instrument panel. The amount of eye movement required to read a display symbol should be effectively zero. Two conditions will interact to degrade performance with the display if figures which subtend large visual angles are used. Eye movement required to scan the data and the apparently large figures used to convey familiar information will combine to stimulate the accommodation response. Incorrect accommodation will interfere with both the use of the displayed information and the view of the outside world. While this is a theoretical interpretation, some preliminary test results do suggest that these assumptions are correct. Experimental examination to assess the influence of the projected size of the displayed information on the use of the helmet mounted display is needed.

The brightness of the display images is extremely important in the high-speed low-level environment. An earlier assessment of the brightness variable considered only night and day use of the displays (1). In a low-level environment, at night or under very dim daylight conditions, the earlier analysis of the intensity variable is accurate. In full daylight, which is the environment for most fixed wing low-level operations, the brightness dimension is more complicated. The terrain brightness range is the source of the complication. Against a relatively homogeneous background the intensity of the display can be set with no adjustment required. Against a non-homogeneous background such as terrain composed of farmland with frequently interspersed small forrested areas and bodies of water, helmet mounted display imagery could be rendered useless for all practical purposes, unless some sort of automatic brightness adjustment is provided. A pilot could not be expected to add to an already heavy workload, the requirement to constantly adjust the brightness of a helmet mounted display. This interpretation should also be more fully assessed by experimental analysis.

The effect of a helmet mounted display on the visual responses was referred to briefly above. If the stimuli presented via the helmet mounted display incorrectly stimulate accommodation, convergence or scan responses, the view of both the environment external to the aircraft and the display can be degraded. The size of the displayed images has been cited as a potential problem, and some difficulty due to size has been cited in field evaluations (4). The same field assessment also reported that the accommodation required to read the display information was different from that required to view the external environment.

If the optical system of the display is misaligned, the accommodation requirement can be other than infinity. The platform on which the optical system is mounted, the helmet, is unstable. In order to make the platform more stable, rigidity and weight must be added to the helmet. These are both undesirable from the point of view of both pilot comfort and fatigue. It was considered highly desirable to determine the extent to which small deviations from collimation might influence the accommodation response of an observer viewing a scene through a beam splitter. A study in which the projected distance of the virtual images was varied from 1.25 meters to optical infinity indicated that the effect on accommodation was small and transitory. This result indicates that though it is desirable to have a good optical system in a helmet mounted display, severe penalties in weight should not be imposed to achieve a perfect system.

Both the overall visual angle subtended by the display and the visual angle of the information displayed, letters, figures and symbols, have not received adequate experimental analysis. It would appear that the overall visual angle of the display should be no larger than the angle normally scanned in eye movements without head movement. The reflex response for a larger area is to move the head. In

a helmet mounted display, head movement moves the information being scanned. The effort required to scan a larger area without head movement could degrade performance, and interfere with mission performance.

BINOCULAR-MONOCULAR DISPLAYS - Most of the helmet mounted displays and sights have used monocular optical systems. A few have used binocular optical systems. There are positive and negative aspects to the design and use of both systems. The optical design and construction of a monocular system are easier than that of a binocular system. However, binocular conflict, whether rivalry or brightness differences in the two eyes, make the monocular system somewhat awkward and unnatural to use. The difficulties are not as obvious in a helmet mounted sight as in a display. In a sight, only a reticle and possibly discrete peripheral signal lights are present. The visual tasks are relatively simple, though the reticle aiming tasks may not be easy. The optical design and construction of a binocular helmet mounted display are more difficult because the alignment for the two eyes must be maintained and instabilities in the image generating device must be minimal and balanced for the two eyes. Once the design and construction problems have been solved, use of a binocular device is much more comfortable, and binocular imbalance problems are not present. The binocular helmet mounted display is the preferred form.

One additional area of concern which has not been discussed is that of buffet. If the buffet is low frequency, a helmet mounted display may not be useable. This is another area which should be examined experimentally.

CONCLUSIONS - A helmet mounted display can provide an improvement in aircrew performance in high-speed low-level operations. There are several unanswered questions regarding the use of such displays in low-level operations. These questions can only be answered by careful experimental analysis. These analyses should be conducted to provide the information which display designers can use in developing the displays.

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DISCUSSION

DR. K.E. MONEY (CAN)

When looking outside the aircraft, and simultaneously seeing a helmet mounted HUD presentation, head rotation will cause a reflex movement of the eyeballs that will stabilise the retinal image of the outside world, but will move (over the retina) the retinal image of the HUD presentation. During the head movement, therefore, one would expect a blurring of the HUD display and also possibly disorientation effects. Have these phenomena been observed and are they serious problems?

AUTHOR'S REPLY

We have not observed such a problem with the helmet mounted sights. However, should there prove to be a problem of this sort in using the helmet mounted designs in which more complex stimuli will be used, we will have the option of using the helmet position-sensing mechanism and the aircraft computers to minimise the blurring to the extent required by either a small delay in the movement of the images, or moving them similar to a saccade. There is also the possibility of using eye movement in combination with helmet position to manage the display imagery.

DR. M.L. WOLBARSHT (US)

We are also thinking of these displays feeding information when the pilot doesn't really see the outside world - infra red sensors for example - so that when he looks in a certain direction what he sees will be appropriate for that direction.

AUTHOR'S COMMENT

A further example is the use of a helmet mounted display in helicopters or V/STOL aircraft so that the pilot can, in effect, look through the floor of the cockpit.

DR. A.J. BENSON (UK)

You rather skated over the problem of binocular rivalry. This worries us in particular when you are presenting real world imagery. How do you see this problem?

AUTHOR'S REPLY

This problem is amplified when real world information is presented and I am aware of some of the problems that have been experienced at Farnborough. It seems most serious when one eye is occluded and receives only display information. There may still be problems with the "see through" system that I have been discussing, especially due to brightness differences in the two eyes when one eye receives environmental plus display information and the other environmental information only.

DR. A.J. BENSON (UK)

In a different luminance and in a different colour?

AUTHOR'S REPLY

Exactly. These are the kinds of problem that we are looking at. A greater problem may be to achieve an adequate display size and one answer with a binocular system may be to cheat a little bit and only overlap a portion of the visual field, so that peripheral areas of the display are seen by one eye only.

COL. R.L. DEHART (US)

The Navy, I believe, are beginning to have experience with helmet mounted systems. What problems are they experiencing - crew comfort, G-loading for example?

AUTHOR'S REPLY

The only operational experience that the Navy has had with helmet mounted systems has been with a helmet mounted sight in which the images presented were a fixed reticle for aiming and discrete lights which signalled "lock-on" of the system being aimed. The pilots who used the system were so enthusiastic about it that they accepted the increased weight and imbalance of the helmet which it caused. A form fit helmet was required for a useable system. The helmet mounted displays are still in the development stage.

We are now working on a binocular display using fibre optics so as to take the weight of the image generating device off the helmet, and we are also trying to maintain the balance of the helmet.

COL. R.L. DEHART (US)

What about vibration?

AUTHOR'S REPLY

I don't think this has been a serious problem, but the information that our friends at Farnborough have generated (*paper 13*) will be important in making decisions about the display design.

DR. J.P. PAPIN (FR)

Le pilote desire une information pour cela il appuge sur une commande. Combien de commandes faut-il prèvoir au minimum?

AUTHOR' REPLY

We do not know exactly how many commands it will be necessary to provide. However, we can estimate that the critical information will be aircraft speed and perhaps attitude. That information should be available on the control stick or on one of the controls which the pilot could easily operate without the requirement to look into the aircraft to locate the call mechanism. The selector mechanism for other less critical information can be located on the instrument panel or console.

RESEARCH ON VISUAL ENHANCEMENT FOR HIGH SPEED LOW LEVEL FLIGHT SPONSORED BY THE NAVAL AIR SYSTEMS COMMAND

by

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SUMMARY

Apart from engineering considerations, the proper emphasis of the various parameters of visual displays in high speed low level flight depends upon the knowledge of the physiological variables in the visual system. Psychophysical tests can best be interpreted in conjunction with a detailed examination of the physiological function of the visual system. A summary of some programs sponsored by the Naval Air Systems Command is given to show our progress in this approach.

An examination of the initial steps of photoreception, the activation of the photopigment rhodopsin by a photon, has suggested a new theory of dark adaptation. The absorption of a single photon decreases the probability that any future photons absorbed in the same photoreceptor will result in visual excitation. (In this theory all of the molecules of rhodopsin in a single outer segment of a rod could be linked by light-initiated movement in rhodopsin). To minimize rod contribution to color recognition of cockpit or heads up displays, light adaptation of the rods might be helpful. This new theory of light adaption suggests that a low intensity of light delivered in short pulses would be more effective than the same number of photons over longer periods of time. The data for this model comes from our program at Cornell University under the direction of Dr. A. Lewis in which resonance Raman spectral analysis is used to measure the changes in the electronic configurations of the rhodopsin molecules during the first few nanoseconds of photoactivation.

After the photoreceptors in the retina have been activated the information is carried through the various neuronal channels to the ganglion cells. The configuration of all the retinal information is completed in the ganglion cell for passage along the optic nerve. The limits of visual acuity depend upon the relation between the receptive field of the ganglion cells and the size and location of the photoreceptors. Models of retinal ganglion cell receptive fields, based on physiological data collected in our program at Duke University under the direction of Dr. M. L. Wolbarsht, suggests that the retina does not preserve spatial information on the contrast phenomena of edges in a point to point relationship; rather the information in the optic nerve is coded in terms of overlapping receptive fields. The information for color and pattern detail travels along somewhat separate pathways from the retina. An appreciation of the details of this coding in the nervous system together with our knowledge of certain visual illusions (such as flicker color) suggests that the cockpit or heads up display systems should emphasize border contrast information at the expense of spectral purity where engineering requirements make such a choice necessary.

The visor used by pilots in all types of missions, including especially high speed or low level flight, often contains filter material which selectively absorbs or reflects parts of the visual spectrum This results in distortion of environmental stimuli and may alter the appreciation of any cockpit or heads up display. The program at the Naval Air Systems Development Center, Warminister, PA under the direction of Dr. G. Chisum, is designed to furnish information on the effects of such filters on the function of the visual system, especially on any degradation or enhancement of visual performance. In a systems approach to the design of a heads up or cockpit display the protective features of any filter must be optimized all together. An important part of this design information is the interaction between the visual system and the display and the adverse stimulus from the environment. A knowledge of the detailed function of the visual system is necessary, in addition to any psychophysical tests which demonstrate visual performance with the specific eye protection filters.

The head and eye tracking system study at the Naval Training Equipment Center in Florida under the direction of Dr. J. J. Kulik is particularly oriented toward the measurement of the helmet mounted (heads up) visual display system as limited by interac-

tion with human capabilities. The purpose of this research is to insure that the movement of visual targets within the helmet display system is properly matched to any possible eye movement. The ideal solution, of course, would be to mount eye tracking equipment in the combat helmet. However, such is not possible at the present stage of the art and efforts are now turned toward optimizing the presentation of data to determine the maximum allowable delay in target movement that is available to the observer, and to study proposed techniques which might shorten delay time.

High speed low level flight often has abrupt changes in direction with attendant high G forces. These are accompanied by changes in visual function such as decreased visual sensitivity, dimming of the visual field, peripheral and central light loss, and even loss of consciousness. Both the visual changes and loss of consciousness are due to inadequate blood supply to the eyes and brain when acceleration produces hydrostatic pressures that exceed cardiovascular capabilities. Attempts to measure blood flow by Doppler techniques are subject to many artifacts especially when the subject is not completely relaxed. The measurements of visual evoked cortical responses may be able to indicate the integrity of the visual system irrespective of muscular activity in the pilot. Our program at the Naval Air Development Center at Warminister, PA under the direction of Dr. M. Cohen is designed to find if the evoked cortical responses can be correlated with the measures of blood flow by Doppler techniques during increased G from acceleration load (under various physiological conditions including strain maneuvers). If such techniques prove reliable, it may be possible to develop a visual evoked response recording system in the helmet to act as an integral part of the feedback in the G suit and assist in maintaining the pilot in good physiological condition during maneuvers characteristic of high speed low level flight.

1. INTRODUCTION

The development of aircraft capable of high speed flights at low levels for long durations has begun to approach the limit of the air crew performance, particularly with regards to the visual system. Although many aspects of the operational problem have been eliminated, or reduced in importance by automation, the implications of the design features imposed by newer aircraft, with regard to visual demands upon the aircrew, have not been changed. Much could be done by automation, but in order to make this possible a better knowledge of the physiological variables in the visual system must be obtained. The Naval Air Systems Command has sponsored several programs which are bound by a common thread to elucidate the ultimate capabilities of the human visual system. The important aspects of each of the separate projects will be described, together with some indication of what bearings this research has on furnishing assistance to the problem of high speed, low level flight as related to the capabilities of the visual systems of the air crew. The programs will be described individually, first with details of the actual research performed and current data, and then relating each individual project to the larger problem of air crew effectiveness.

2. PRIMARY EVENTS IN VISION (Lewis)

In order to have a proper basis for visual displays, the fundamental principles underlying certain aspects of visual physiology are being investigated. Specifically the primary events in rod vision must be known before we can understand the basic mechanisms of dark and light adaptation. This is of specific importance since the rod contributions to color vision in the mesopic range could cause ambiguity in color recognition of cockpit and heads up displays. Through an understanding of how this process works, some control is possible to reduce some of the ambiguities associated with color recognition in this range. In order to control the contributions of the rods it is important to understand the initial molecular processes that underlay the activation of these cells at various lightlevels.

The primary molecular light processes involved in the absorption of a photon by the photopigment and its conversion into a neural signal (which begins the transfer of information through the retina to the lighter visual centers) was studied by high resolution resonance Raman spectra of rhodopsin, isorhodopsin, and photostationary state mixtures containing a high percentage of bathyrhodopsin. With this technique, new spectral features have been detected. These have not been observed previously due to poorer resolution of the experimental equipment as compared with that used in the present program. The bands observed in the photostationar state spectrum can be identified from resonance Raman spectral results on pure rhodopsin and isorodopsin solutions as well as on alterations in the photostationary state mixtures of the pure compounds. The features in these spectra are invariant from $20^{o}K$ to $150^{o}K$, indicating that the structural alterations in the protein component of retinal occur in steady state spectra even at $20^{o}K$. Those changes are consistent with a model of excitation previously proposed (1). In addition, we have found that certain features in the photostationary state spectra were altered by using a D_2O medium for suspending the membrane fragments.

By several improvements in our spectral equipment, we have been able to obtain the solution of 2 cm^{-1} as opposed to the usual resolution of 10 cm^{-1}. This five-fold increase in resolution has allowed identification of all bands present in the spectrum, and has shown many special features of bathyrhodopsin previously undetected.

The experiments were performed on bovine retinas and as shown in the data the exciting light was 500 nm which is generated by a dye laser. Only 10 percent of the sample was photoconverted or destroyed during the Raman resonance measurements. Figure 1

shows the spectrum of purified bovine rhodopsin at 95°K obtained with 3mw, 4812.5 nm. excitation. In figure 1B, the same excitation was used but the sample was now simultaneously illuminated with an 18mw, 58 nm pump laser beam. This changed the concentration of bathyrhodopsin from the 60% in Figure 1-A to about 30% in Figure 1-B. This allows identification of the 922, 1019, 1208, 1324, 1537 cm^{-1} bands that were not detected previously in either low temperature or flow experiments. These bands are absent in the spectrum of protonated Schiff bases of 11 cis-retinal. Thus, it is evident that bathyrhodopsin is not unique in having vibrational modes between 800 and 900 cm^{-1}. The identification of these bands and similar ones in the other molecules under various conditions allows us to model changes in the shape of the molecule during the various stages of excitation. The work can be summarized as suggesting that the chromophore in bathyrhodopsin must be in a comformation which can be formed from either the 11-cis or the 9-cis configurations and can relax to an all-trans conformation. All our data indicates that this is the important, very crucial step of visual transduction.

As mentioned above, we plan to continue this work in order that an understanding of the fundamental molecular processes controlling light adaptation in rod cells can be used to possibly reduce ambiguities in color recognition in cockpit and heads up displays, or control psychophysical phenonema such as light and dark adaptation, or visual sensitivity changes as large as flash blindness in relation to the amount of visual pigment bleached or regenerated. Also, it may identify molecular processes that may lead to an appreciation of the color associated with picosecond laser pulses in the infrared, and lastly, it may indicate how the photic energy can be converted into chemical energy in as short as one picosecond.

On the basis of these measurements, Lewis and Wolbarsht (2) have proposed a model which couples the loss of visual sensitivity in light adaptation to an allosteric change in the electronic conformation of the protein part of the rhodopsin molecule. This is analogous to the electronic changes that occur in hemoglobin when it binds or releases oxygen. These rearrangements influence the active part of the molecule in hemoglobin (heme moiety that binds the oxygen) and in rhodopsin the chromophore retina, which gives rise to excitation after a photon is absorbed.

In hemoglobin the allosteric forms of the proteins change the molecule's response to oxygen binding as a function of the environmental oxygen tension. For example, when the first oxygen molecule is bound to heme, the electronic levels in the protein change to allow a second molecule of oxygen to become bound at a lower environmental oxygen tension, and so progressively in the same direction until the heme has bound its full capacity of four molecules of oxygen. As the fourth oxygen molecule is bound, the hemoglobin molecule changes its overall electronic configuration so that a very great drop in environmental oxygen tension is required before the first molecule of oxygen can be released. The release of the first molecule of oxygen changes the electronic configuration of the protein in such a way that the second oxygen molecule can be released, even though the tissue oxygen tension is still higher than when the first was released, and these changes in the protein go on until the fourth is released. At this point, the protein part of the hemoglobin changes appropriately again and requires a very much higher oxygen tension before the first oxygen molecule can be rebound. It is obvious that such changes must take place in hemoglobin to bind the oxygen in the lung and release it to the tissues. Indeed, such changes are almost expected once such a mechanism has been suggested. However, the allosteric change in rhodopsin has a slightly different type of action.

When a molecule of rhodopsin absorbs a photon, the chromophore is electronically raised into the activated state. The electronic state of the protein part of the molecule is then changed by interaction through the linkage to the chromophore. This probably occurs by electron delocalization produced on the charged terminal groups of the neighboring amino acids of the ε- linkage of lysine. It also seems that when one molecule of rhodopsin has its electronic environment altered it will in turn influence the electronic environment of nearby rhodopsin molecules. There are many molecules of rhodopsin in each disc of the outer segment. Recent data of Lewis (1) suggest that if a single rhodopsin molecule is placed in the activated state (and goes on to become bleached) this affects the electron distribution of the neighboring molecules. This change may lower the probability that the neighboring rhodopsin molecule will give rise to visual excitation after absorbing a photon of light. This model has been carried further by Lewis and Wolbarsht (2) who assume that the entire rod outer segment forms one compartment in a modified form of Wald's compartment hypothesis (3). All the rhodopsin molecules in this compartment (the whole outer segment) are in each others' electronic environment. A further analysis of this model shows that it can meet the requirement that there be a shift in photon requirement with light adaptation.

The nature of the link between (or binding) rhodopsin and visual transduction cannot be specified or activated at the moment. It may be the release of calcium ion, a change in conductance of the outer segment, or even (which we feel is the most likely) a change in the internal pH of the cell following proton binding by the protein. Such changes in the internal pH of the cell could be the first step to visual excitation by influencing transmitter release in the rod (or cone) synaptic region. Interaction between the rhodopsin molecules may be mediated by proton migration or some similar phenomen. As conformational changes in proteins such as an allosteric rearrangment can take place in nanoseconds or less, no time lag would be seen on the physiological time scale. It is assumed that these conformational changes remain until all of the bleached rhodopsin molecules are isomerised back into the active form. This preserves the decrease in visual sensitivity resulting from the bleaching of single molecules given by

Wald's original model (3), but the present model allows a greater amplification factor, and also accounts for the variation in quantum requirement with bleaching (or regeneration) of visual pigment.

3. VISUAL ACUITY AND RETINAL ORGANIZATION (M. Wolbarsht)

After the photoreceptors in the retina have been activated by photo absorption and stimulate the next neural cell, information is carried to the higher visual centers by the various neuronal channels. The spatial configuration of the stimulus, along with all other visual parameters passing through the retina, is assembled at the ganglion cell level. All coding of information is then arranged in patterns by the particular ganglion cells involved for passage along the optic nerve to the higher visual centers.

The limits of visual acuity have been shown to be dependant upon the relation between receptive fields of the ganglion cells and the sizes and locations of the photoreceptors (4). Models of retinal ganglion cell receptive fields based on the physiological data collected in this program suggest that the retina does not preserve spatial information or edge contrast data in a point to point relationship. Rather the information in the optic nerve is coded in terms of overlapping receptive fields.

Most theories of visual acuity ascribe the ultimate visual acuity attained to the retinal image size as related to the size and shape of the photoreceptors in the retinal mosaic (5). The details of the image on the retina are such that the wave properties of light itself determine the intensity distribution, that is, something so distant in visual space that it is a point source from the standpoint of geometrical optics. A star, for example, is focused on the retina not as a point but rather as a diffraction-limited image. The details of the diffraction limited-image are then dissected by the receptors.

The most important aspects of the retinal mosaic are the minumum center-to-center spacing of the receptors, their size, shape, and refractive index, all of which determine their waveguide properties. The majority of the analyses of visual acuity in relation to the retinal mosaic have been concerned with how the retinal anatomy is matched to the image on the retina as calculated and measured with point spread functions and modulation transfer coefficients derived from a spatial frequency analysis. Models based on such analyses contain an implicit assumption that information transfer through the visual system presents a point-to-point topographical representation of the retinal receptor mosaic up to the cortical level. Thus, as an end result, each retinal receptor is represented in the cortex by a single cell or group of cells. In these models the responses of the cortical cell contain coded messages representing the intensity of the light on the appropriate receptor. However, the details now available of the anatomical structures in the human visual system and the functions as presently known of any of the cells within the visual system are not compatible with a strict point-to-point representation for information transfer about location of images on the retina.

In much of the retina, each ganglion cell is connected to large numbers of receptors to produce overlapping receptive fields. In the foveal region (the center of the retina) where the visual acuity is the best, the histological analysis of the retina suggests that there is nearly a one-to one relationship between receptors and ganglion cells with, however, slightly fewer ganglion cells than receptors (6). However, this agreement with a point-to-point representation maybe more apparent than real.

Although the standard for visual acuity is usually considered to be a minimum visual angle of one minute of arc, this performance can be bettered to 0.5 minutes of arc by many individuals, presumably with the same type of retinal makeup (5). Also, within the visual system there are neural mechanisms which could act to increase contrast by amplifying small differences in intensity (7). This process could aid in the detection of the borders which determine visual acuity. It has been the purpose of this project to examine the basis for visual acuity and especially to consider what role the organization of the neural system (that is, its anatomy and coding function as now known) plays in determining the ultimate limit of visual acuity. It is possible that the distortion of the information by receptor to ganglion cell connections may form the fundamental and ultimate limit of visual acuity.

In a model of the human visual system which has point-to-point representation there must be as many ganglion cells as receptors and the connections between them must be simple. A suggestion that a high degree of visual acuity can be attained without this sort of organization can be found in some animal eyes. For example, in hawk and eagle eyes the optics and visual acuity are as good as in humans, if not better (8, 9, 10) However, in the eagle and hawk foveas, the reeeptor to ganglion cell ratio is quite different from that in the human fovea. In both birds there are at least three and possibly 10 receptors to one ganglion cell (Miller, 1976; Fite and Rosenfield-Wessels, 1972). This indicates that good visual acuity does not require as many ganglion cells as receptors. Furthermore, in these visual systems at least, point-to-point representation of the receptor stage throughout the visual pathway cannot form the basis of visual acuity.

There is an additional consideration in computing the ratio of receptors to ganglion cells as an indicator of information processing for visual acuity: ganglion cells are not all the same. They are not equivalent to each other in their function. On the basis of these differences in function they can be grouped into several distinct categories. As some categories may not be involved with visual acuity, the ratio of

ganglion cells to receptors for visual acuity may be far less than is calculated from simple anatomical examinations. Ganglion cells carry many different types of information in a sort of time sharing relationship. They carry the intensity information required for border contrast along with information about color contrast, for information can only leave the retina when it is funneled through the ganglion cells.

It is obvious that both visual acuity and color information are changed as they are encoded by the neural networks in the retina. This process exaggerates certain features, and eliminates, (or at least compresses) other features. Thus, border and color contrast are increased. In some aspects the image on the retina is only considered by the visual system as the basis for an effort to reconstruct the source in visual space rather than itself to be accurately perceived by the higher visual centers. It is easy to understand how this information distortion could lead to certain types of visual illusions or even inaccuracies in perceiving visual space. If the shapes of the functions by which the information is distorted in the visual system were known, then a minimum band width visual display could be manipulated to emphasize a desired feature. Also, bandwidth in the display could be conserved if visual features that were known to be ignored by the visual system could be eliminated from the display (if desired) presented in such a way that the retina would emphasize them.

Figure 1 shows the photon distribution of the diffraction pattern of the retinal image of a point, and in Figure 2 are the diffraction images formed by two adjacent points as the separation between them is changed. At 2.5 mm, the separation of the centers of the two points can be distinguished as separate by many people. However, due to chromatic aberration, a white light image would give a quite different photon distribution from a monochromatic source. Yet, both are discriminated in approximately the same way. It is obvious from this that the light distribution of the image on the retina is not the only important thing for visual acuity. Rather it is the neural network in the retina that treats the information.

Our work has indicated that all retinal receptive ganglion cell fields are quite large. This indicates to us that point to point representation of all retinal locations is not the basis of the type of acuity discrimination shown in Figure 2.

Some sample data on the receptive fields of retinal ganglion cells are shown in Figures 3 and 4. These figures are from a Y cell, which type is generally agreed to be the major pathway for visual acuity information flow. Although the recordings shown are from a cat, similar recordings have been made from monkeys, and presumably such cells are also in the human retina, especially in the foveal region.

It seems obvious that an understanding of the coding in the ganglion cell will aid in our understanding of visual illusions and figure color, and also will allow us to optimize cockpit or heads up display systems as reqards border contrast information.

Our information is sufficient at this point to suggest that where engineering requirements make a choice between spectral purity or border contrast information as part of a heads up display system, border contrast information should be chosen. This will allow terrain features or other types of information to be more quickly assimilated and selected features emphasized by removing certain types of detail that the visual system will only recognize as clutter in the visual presentation.

4. VISUAL PERFORMANCE OF AIRCREW PERSONNEL UNDER SPECTRALLY SELECTIVE FILTER CONDITIONS (G. Chisum)

The visual performance of the aircrew personnel in high speed low level flight is hampered by a variety of problems. One of these is the distortion of the visual scene by various airplane components, such as the cockpit screen and any individual visors. The Naval Air Development Center Project No. WR041-0110101/DG1XX addresses this problem directly. The selective absorption or reflection of parts of the visible spectrum can result in distortion of the visual environment. It may also alter the appreciation of any cockpit or heads up display by changing the background visual environment. This program is designed to furnish information on the effects of such filters on the functions of the visual system, especially on any degradation or enhancement of visual performance.

The systems approach to the design of the heads up or cockpit display must take account of the presence of any filter and its protective features, so that the overall combination can be optimized. An important part of this design information is the interaction between the visual system and the display, in combination with any adverse stimulus from the environment. Thus, a knowledge of the detailed function of the visual system is necessary, in addition to any psychophysical tests which demonstrate the changes in visual performance with specific eye protection filters. Ideally, the filters should be chosen so that not only are the unwanted aspects of the environment minimized, but also that the desired features of the visual display be emphasized. This could be especially valuable in any combined presentation of the external environment together with a heads up (or helmet) display system with a prerecorded trip map of the flight (mission) in which selected features are projected.

5. MONITORING EYE MOVEMENTS FOR WIDE ANGLE DISPLAYS (J. Kulik)

Head and eye tracking systems are being investigated in order to determine the pilot's areas of interest in his visual environment during high speed, low level flight. The purpose of monitoring eye position, and the area of interest is to insure that the selected portion of the display has the highest possible detail in proportion to that of the remaining portion of the presentation at the time the pilot desires it. It is difficult from engineering and economical considerations for all portions of the visual presentation to be at the highest level of resolution at all times. However, by ascertaining where the pilot is looking, the high detail level presentation (insert) can be made in selected portions of visual space at the expense of other less well appreciated points. Thus, an eye tracker can assure, that as the fovea is moved around to different parts of visual space, the detail in the presentation of a projection in visual space will be tailored to fit the capabilities of the visual system. This could result in a considerable saving in terms of allocation of system band width.

Training for low-level, high speed flight, and target acquisition is either dangerous or costly using combat ready aircraft, particularly in terms of the amount of flight time devoted to the actual training. Traditionally training has been mainly oriented towards simulation devices. As a variety of events occur around the pilot, farily wide field-of-view visual displays are needed for effective training. Two technologies are currently competing to provide such wide-angle displays: a mosaic of large cathode ray tubes around the cockpit to present an out-the-window image of the world; and projected images on a dome surrounding the cockpit. In order to train for these tasks effectively, high resolution targets (either on the ground or in the air) must be presented. The manner of obtaining this level of resolution in a cost effective manner is the subject of the present research and devlopment work.

The CRT systems in the Air Force's Advanced Simulator for Pilot Training and the Simulator for Air-to-Air Combat present images of uniform resolution on each CRT face, with wider fields of view achievable by adding more such channels, yet these display systems are expensive and delicate. Dome projection systems have approached the problem of high resolution images by having at least two projection channels - one to display a low-resolution background spread over the entire field of view, and a second to insert high-resolution images of objects of interest. Currently such systems can present fairly detailed images of objects if the location of that object relative to the pilot is known.

Ideally, the ability of a display system to produce high-resolution images of limited size should be directable by the needs of the pilot being trained, i.e., he should be able to examine any object in his visual world (external to the cockpit) in sufficient detail to identify it. The Naval Training Equipment Center is currently developing an area-of-interest computer image generation system with a variable level of detail scene output. This would allow a computer generated image of non-uniform level of detail with the area of greatest detail density placed wherever selected. A helmet mounted projector for dome images is being investigated to minimize the distortions arising from the differences of position of the pilot's eyes and the projection source. Both types of display must allow the subject to determine the location of the high-detail area of the displayed image by his point-of-gaze. The real problem is the mechanization of such a capability which involves the tracking of both the position of the pilot's head and eyes, and real time calculation of the direction of gaze. Fortunately, some of this problem has been solved as there are operational head trackers to give the position of the head in three rotational degrees of freedom to an accuracy of about 0.5 degrees by means of nutating three axis, magnetic fields with helmet sensors. The system delay is less than 20 milliseconds, which is sufficient as head velocity is less than 300 degrees per second.

Tracking the position of the eyes poses more of a problem, even though the high accuracy achievable by some techniques of eye monitoring (11) may not be needed. Also, the complex optical arrangements needed for these measurements are not desirable. Simple infrared detectors can monitor the horizontal movements of the eyes within a degree. Following vertical eye position requires some development work, for infrared detectors can monitor the position of the lower or upper lid, but these move with different dynamics than the eyeball. Regardless of the technique used, eye position in two rotational degrees of freedom must be known to determine the point of gaze.

Of more technical interest is the need to predict the new point of gaze as a change is detected. This is required by the sequence of operation of the flight simulator in which the positions of the various controls in the cockpit are iteratively sampled. The proper response of the aircraft to these inputs is then calculated and simulated. The newer systems have 30 samples per second. In computer image generated visual display system, changes in position of the aircraft are calculated and made the basis for the image by an appropriate picture processor. The processors operate at 30 Hz but take three frames (about 100 milliseconds) to produce a new image. This means that delay from pilot input until the responses of the aircraft are displayed can exceed 120 milliseconds. However, the Naval Training Equipment Center system can almost halve that time by operating at 60 Hz.

Obviously for an area-of-interest image generation system, any prediction of the coordinates of a new point of gaze while the eye is moving will reduce the delay before the correct image appears. Several metrics for predicting the new point of gaze while the eye is moving are under consideration, but few data exist that could give an indication of how accurate they are. The velocity wave-forms of saccades are roughly symmetric - suggesting that a peak velocity could be used until it levels off at velocities

of 550 to 750 degrees per second. The velocity at the peak positive acceleration has also been suggested as a metric for prediction. Both of these measures are relatively easy to obtain, but no data exist correlating them with the resting position of the eyes after a saccade. However, some data does indicate a continuing variability of peak velocities and accelerations for saccades of fairly fixed size (12, 13). Possibly the metric selected could be stabilized by averaging or filtering.

The amount to which head and eye position can be accurately (and unobtrusively) monitored will determine the feasibility of using a high-level of detail area visual display controlled by the pilot's interest. How accurately and early the resting point of gaze can be predicted during an eye movement will affect the appearance of such a visual display. Although the proper appearance of the area of interest will be delayed by some amount - and that is yet to be determined - how aversive or disruptive this delay is must also be determined. Long delays in manual control systems certainly affect pilot control performance (14) but there is no comparable data for visual target tracking. However, tracking is not really the problem. Rather, we are concerned with the pilot's selection of where he would like more detail in the visual scene. Any delay of that information might be noticed and could disrupt the scan pattern in target acquisition tasks.

The importance of delayed presentation of information during scan patterns is now under investigation at the Naval Training Equipment Center. A two-gun CRT is used to present a fixation point and a moveable target, and delays of various durations are inserted into the movement of the target. The task, initially, is to move the eyes in saccades to selected positions at various distances from the fixation point, and to report if the delayed appearances of the target was appreciated. Normal forced-choice psychophysical procedures are used to determine thresholds as a function of the size of the saccade, the size of the target, and its relative contrast. Preliminary, but encouraging, observations indicate that delays below 100 milliseconds are not very noticeable.

The delayed appearance of a part of a visual scene which tracks eye position may not be well appreciated because of saccadic suppression - the attenuation of vision during rapid movement of the eye. Any saccadic suppression will make these areas of targets display systems more acceptalbe. Some estimates of the time course of saccadic suppression (taken from Volkman, 1976) indicate a period of 100 to 150 millisecond from the start of a saccade until the visual thresholds are again normal. Any changes in the visual scene during that period will be less noticeable than normal. The important questions are how much, and is that enough. Presently there are no answers, but reviews of the suppression literature (15, 16) are encouraging. Only movements in part of the display, which are large relative to the size of the saccade, are noticed, (17, 18). Thus, for a computer generated area-of-interest display as movement is minimized in extent, delay may be less of a problem.

The size of the high level of detail insert is also important in the design of a moveable area-of-interest display. It probably need not exceed foveal dimensions, as visual acuity falls sharply outside the fovea. Yet much data has been accumulated that indicates that information is used from larger areas (6°-8°) at suprathreshold levels. The size of this "functional field of view" -where information can be extracted from a visual display - seems dependent on the density of irrelevant items in displays containing descrete elements (19), and on the size of the scence to be processed (20). Is is probably a function, also, of the sort of visual information the observer needs from a given scene. From this it is quite likely the display will be improved if an area larger than the fovea has the greater resolution.

The allocation of system bandwidth within an area-of-interest display which tracks the point of gaze is another important design consideration. It would be helpful to reduce the total system bandwidth needed for wide angle display systems sufficiently that special purpose components would not be needed. Indeed, this was the motivation for developing the present area-of-interest displays. A uniform high resolution is used across the insert with a uniform lower resolution for background. This need not be the case. Computer image generation systems change the density of pixels along a raster scan line, and an optimal distribution of pixel density about the point of gaze has not been found. A non-uniform distribution would conserve bandwidth in the sense that it would allow more resolution where it can be used by the eye, but the nature of its fall-off about the center of gaze depends upon a number of factors. Clearly as the center of this area must respond to eye and head position, the accuracy with which this can be done will determine how large the insert must be. This and the cost of display equipment will determine the bandwidth allocation within the display, and ultimately, the image resolution. Hopefully, knowledge about the information processing of human observers can place some boundries on how the bandwidth should be spread with regard to the visual axis.

6. <u>CONTINUOUS EVOKED RESPONSES AS AN INDICATOR OF "G" TOLERANCE</u> (M. Cohen)

High speed low level flight often has abrupt changes in direction with attendant high G forces. These high G forces are accompained by changes of visual function, particularly decreased visual sensitivity, dimming of the visual field, development of peripheral and central scoatomas, and even blindness. All these changes in the visual system are due to inadequate blood supply to the eyes and brain when acceleration produces hydrostatic pressures that exceed cardiovascular capabilities. We are developing

a technique to measure the evoked cortical responses as an indicator of G tolerance. The initial experiments have been designed to find which evoked cortical responses can be correlated with changes in blood flow as measured by Doppler techniques. The blood flow is modified by increases in G from acceleration, and, also, various physiological conditions including straining maneuvers. The purpose of this program is to develop a visual evoked response recording system helmet to act as an integral part of the feedback system in the G suit. This will assist in maintaining the pilot in good physiological condition during the maneuvers characteristic of high speed, low level flight.

Modern high performance jet aircraft are capable of generating and sustaining accelerative forces that far exceed the tolerances of their operators. The downward (G_z) loading of blood in the heart-brain hemodynamic column can exceed the upward forces generated by the action of the heart. This results in blood pooling in the legs and abdomen. while the eyes and the brain are deprived of freshly oxygenated blood; loss of visual sensitivity, first in the periphery and then in the central areas, can be followed by total blockout and unconsciousness, all in rapid order.

The 280 mm heart-brain hemodynamic column produces forces of approximately 280 gm. with normal gravity. The heart brain column is roughly equivalent to a column of Hg 20.6 mm in height. As the peak systolic pressure of blood at the heart is about 120 mm Hg, bloodflow to the brain would cease in an unprotected and uncompensated subject at 5.8 G_z.

Normal intraocular pressures are 20 mm Hg or less. Thus, bloodflow to the retina should cease at about 1 G less than when the brain itself is deprived of oxygenated blood. As the visual changes generally precede the loss of CNS functioning, visual criteria for human tolerarce have often been adopted.

Animal studies have shown that general anoxia affects the more central parts of the visual pathways first, beginning with the cortex, and progressing to the lateral geniculate nucleus, to ganglion cells, to bipolar cells, and, finally, to the retinal receptors. However, during G_z acceleration, ischemia is first manifested in the retina where as the local arterial pressure falls, the high intraocular pressures of the order of 20 mm Hg cause occlusion of the blood vessels beginning with the capillaries. The ischemia occurs first in the periphery of the retina because the caliber of the capillaries generally decreases towards the periphery (Ward, 1968). Thus, the loss of peripheral vision, progress to loss of central vision and blackout, may be attributed to retinal ischemia. These retinal events are considered to be precursors of unconsciousness due to cerebral ischemia.

This description of the cardiovascular function of unprotected and uncompensated human subjects in acceleration environments represents only a first order approximation; the real situation is by far more complex. Nevertheless, it is sufficient to allow examination of some currently employed methods for enhancing human G tolerance.

One simple method would be to reduce the height of the cardiovascular column. Placing the subject on his back replaces the G_z (head to toes) accelerative forces by G_x (chest to spine) forces. In this position the subject can tolerate more than an 11 G on the airframe. Enhanced G tolerance also results when the blood is prevented from pooling in the lower extremities and the abdomen. This increase in the circulating blood volume results from inflation of the bladders in a conventional G-suit and provides between 1.5 and 2.0 G additional protection. Straining maneuvers, in which the subject exhales against a closed or partially closed glottis (the L-1 and M-1 maneuvers), increase intrathoracic pressure, diminish blood pooling, and provide about 1.0 to 2.0 G additional protection.

It is extremely important to be able to evaluate the degree of G protection afforded by all methods. Traditional evaluations have relied on behavioral and subjective data based on:

1) changes in the apparent brightness of a series of lights,

2) detection of randomly timed presentations of lights in various parts of the visual field.

3) Manipulation of the positions of lights to indicate the limits of the visual field.

4) observations of ocular motility to lights presented at random positions.

In addition to these behavioral tests, an objective physiological indicator, the Doppler measurement of blood flow velocity in the superficial temporal artery has been employed. This non-invasive technique has been quite promising. Doppler flow velocity measures can provide objective criteria for human G tolerance. However, interpretation of the data is sometimes difficult, for those signals depend on the position of the sensors relative to the underlying arteries. This relation can be disturbed under acceleration, particularly when coupled with the straining maneuvers L-1 and M-1. Further, the Doppler techniques do not have the same margin of safety provided in subjective tests in which vision fails before the bloodflow to the brain is impaired.

The behavioral measures of G tolerance do have a margin of safety afforded by the intraocular pressure which terminates vision before cerebral function is impaired. However, these are behaviorally invasive, for when subjects perform the required visual tasks, simultaneous performance of other, piloting-related, tasks is hindered. Also, the behavioral measures are frequently unstable, often providing tolerance limits that differ by as much as 1 - 1.5 G from test to test.

It would be desirable to obtain methods for evaluating G tolerance that have the following characteristics:

1) reliability and reproducibility.

2) physically and behaviorally, non-invasive.

3) objective.

4) relatively insensitive to experimental artifacts.

5) give rapid, on-line, real-time discrimination.

6) have a margin of safety for determining G tolerance without undue risk of approaching unconsciousness.

The objective measures of the integrity of the visual system during retinal ischemia appear to have a potential for meeting these criteria.

It has been demonstrated that visually discriminable photic driving of the filtered EEG follows the frequency of the stimulus. Although all subjects did not demonstrate these phenomena, the results are encouraging. Subject were exposed to accelerative forces in the human centrifuge while measures of peripheral light loss, photic driving of the EEG, and ophthalmoscopic observations of the retinal arterioles were obtained. Ophthalmoscopically observed collapse of the retinal arterioles was associated with both loss of photic driving on the EEG and peripheral light loss. Blackout coincided with systolic collapse of the arterioles. In this study, photic driving appeared to be lost approximately one second before the subject signalled grayout (dimming of the peripheral visual field). Electrophysiological measurements may give other objective tests for G tolerance.

Visual evoked responses (VER) recorded from scalp electrodes constitute a non-specific cortical response to light that does not necessarily stand in a fixed relationship to conduction along the clasical anatomic visual pathways. For example, cortical and subcortical injury to the occipital lobes by crushing or ablation is followed by an immediate decrease in the amplitude of the VER.

The Electroretinogram (ERG) consists of a negative a wave generated by the retinal receptors and a positive b wave reflecting activity of the higher neural layers of the retina and may provide an objective measure of retinal ischemia and G tolerance. The averaged ERG is much easier to detect than VER. However, as stimulus luminance decreases the ERG virtually disappears, while the VER remains. Thus, the ERG may provide a more sensitive index of retinal functioning than the VER. If the sensitivity of ERG to G forces parallels its sensitivity to decreased stimulus intensity, the ERG may provide an excellent indicator. In fact, Ward has observed that the amplitude of the ERG b wave fell by 40% in anesthetized beagles exposed to 1.5 G_z and disappeared completely with exposure to 3.0 G_z. Unfortunately, equivalent research has not yet been conducted with human subjects, and the value of the ERG as an endpoint remains to be determined.

Recent advances in bio-electronics, such as high-gain steady-state lock-in amplifiers, fast Fourier transform techniques, and improved real-time digital computer processing methods have combined to make feasible the continuous, real-time analysis of small amplitude bioelectrical signals that, in the past, could not be recovered from background noise. Since changes in visual function should provide a reliable indicator of G tolerance, and since both the visual evoked cortical responses and ERGs have been shown to provide reliable indicators of visual functioning, it appears that time is now ripe to exploit these techniques in the determination of human tolerance to acceleration.

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Evoked cortical responses as an indicator of G tolerance (M. M. Cohen).

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9. FIGURES

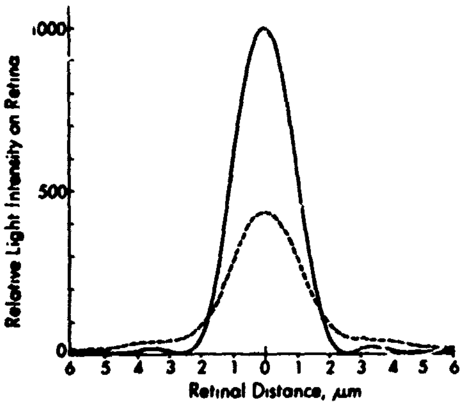

Figure 1
Intensity distribution of the difraction pattern in the retinal image of point source. The solid line shows the Airy disk for a monochromatic source at 560 nm. The dashed line shows the intensity distribution for a point source of white light at the same intensity in focus at 560 nm. Adapted from Le Grand (5).

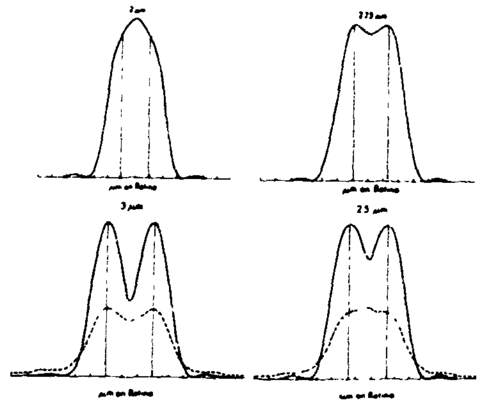

Figure 2
Intensity distribution on the retina of the image from two adjacent point sources of light. The solid lines show the algebraic sum to two monochromatic (λ= 560nm) point sources which individually have the same retinal image of the point sources as shown in Fig. 2. The dashed lines are for white light. A separation of 2.5 µm gives the image corresponding to a visual acuity of 6/3 (20/10). At this separation there is a very small dip in the central intensity distribution of monochromatic light. For white light sources there is no dip.

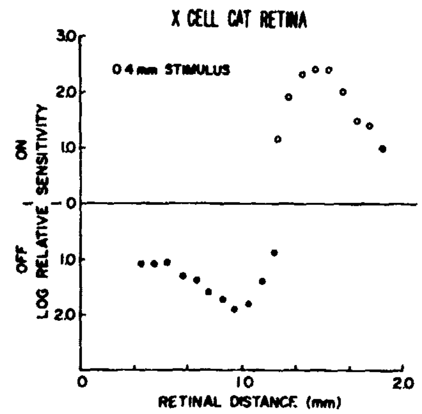

Figure 3

Sensitivity profile of an X type ganglion cell in the cat retina. The data points indicates the intensity required to give a criterion response. The ON response in the center has a dome shaped sensitivity profile. The stimulus is 400 µm on the retina, or approximately 2 minutes of arc in the visual field. The sensitivity profile of the peripheral OFF response should be compared with the central ON response loss of sensitivity with distance. More information on the central ON response is given in the Ricco field plot in Figure 4, which suggests that the top of the sensitivity profile should be flatter.

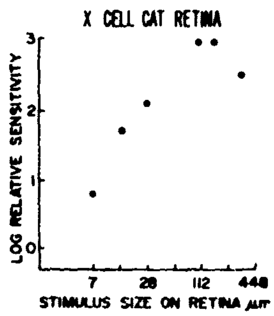

Figure 4

The Ricco field plot (Area X log intensity). The data points indicate the intensity required to give a criterion response for the ON response of a cat retinal ganglion cell (X type). The sensitivity profile of the central ON and peripheral OFF responses of this cell are shown in Figure 3. This Ricco field plot shows complete integration within the central ON response for approximately 100 µm. The fall off of sensitivity with increased stimulus area is probably due to the recruitment of inhibition from the antagonistic surround.

HUMAN FACTORS IN HIGH SPEED LOW LEVEL ACCIDENTS - A 15 YEAR REVIEW

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The Canadian Forces introduced the CF 104G into Squadron Operation in 1963 and since that time these aircraft have operated in the high-speed, low-level environment in both the strike/reconnaissance and tactical support roles. Fifty-seven accidents involving these aircraft are reviewed with regard to cause factors. Marginal weather appears to be the one most significant factor contributing to low-level, high-speed accidents; however, several human factors such as visual contrast problems, fatigue, stress, reaction time, "mission completion" syndrome, inattention and task overload were identified. Aspects of accidents which typify human factors problems are described. Suggested possible preventive measures are outlined.

The Canadian Armed Forces have been flying aircraft in the high-speed low-level (HSLL) operational mode for the past 17 years. The CF 104 operated in Europe with NATO for nine years in the strike/reconnaissance role and, more recently, for six years in the tactical air support role. In addition, the Canadian Armed Forces have also utilized the CF 5 in the close air support role for the past eleven years. During these operations, it has become clear that even with effective aircrew operational training and a vigorous flight safety programme, the high speed, low level role was dangerous and demanding - resulting in what appeared to be a significantly high rate of loss of aircraft and aircrew.

The present survey of high speed low level accidents confirms the findings of a five-year survey completed by LCol I.H. Anderson in 1969, (1) who concluded that, although the cause of most accidents in this environment cannot be absolutely determined, judgement, decision making and available reaction time are factors which almost surely have contributed to the accidents. This survey is an attempt to more clearly identify the human factors associated with HSLL flight and to make recommendations which may enhance flight safety in this role. The following mission descriptions illustrate the task workload and complexities facing aircrew involved.

Strike. A typical strike training mission in a CF 104 was as follows. A preplanned route, chosen on the basis of forecast weather, was flown at 500 feet, 450 knots (800 feet during bird season, April to October). The last leg of the route was flown at 50 feet above ground and 550 knots until the simulated nuclear weapon drop. If deteriorating weather was encountered, the pilot was permitted to climb to 2,000 feet above ground level and complete the route using ground mapping radar; the weapon could be dropped "blind". Target procedures were clear-cut in that the prime considerations were to arm and drop the weapon.

Reconnaissance. Reconnaissance missions were flown at 500 feet, 420 knots. Routing and the target for each mission were different, and therefore, a new map was prepared for each. Where possible, missions were flown in conjunction with ground force exercises in progress - hence some external pressure existed to reconnoitre a particular target at a particular time and hence some psychological pressure could exist to challenge deteriorating weather. Reconnaissance of targets of opportunity was encouraged.

With the requirement to acquire visual contact with the target, reconnaissance pilots would be more prone than their strike pilot counter parts to remain VMC below cloud. A pull-up into cloud generally resulted in an aborted mission.

Pilots were trained to rely upon their visual observations and utilize elements of essential information (EEI) cards. The aircraft mounted cameras were treated as a back-up capability. Last minute decisions at the target included which cameras to utilize, exposure times and camera settings in addition to flying the aircraft and making mental notes. Some pilots resorted to flying left-handed and using their right hand to record information on their EEI cards.

Tactical Air Support. The most demanding role assumed by Canadian CF 104s is the tactical air support role. Missions are planned at an altitude of 500 feet and a speed of 420 knots. Since these missions are flown in support of ground forces, little or no flexibility exists as to the target. The route to be flown is pre-planned based on forecast weather and known threats (e.g. surface-to-air missile sites). Aircraft are usually armed with a mixture of ordnance - hence the pilot must make airborne decisions as to which weapon to employ.

When operating in conjunction with a Forward Air Controller (FAC), the pilot flies to a pre-determined area by means of a pre-planned route. Once in the area, the FAC calls target location to the CF 104 pilot by means of a map reference. While flying at 400 knots plus and an altitude of 500 to 1000 feet, the pilot refers to his 1:250,000 map, locates the target, determines his route to target, decides upon the weapon to be employed and determines his escape route. Each weapon has its' own envelope and therefore, the speed, type of delivery (e.g. level, 10, 20, 30 degree dive angles), foul lines (for richochets) and release points vary with each weapon.

Whereas the strike and reconnaissance missions were flown as independant aircraft, the tactical air support missions are flown as formations of two, three and four aircraft. The formation leader is responsible for navigation and terrain clearance while the wingmen are responsible for station keeping and lookout for aggressor aircraft.

METHODS

All CF 104 accidents from 1963 to early 1979 were reviewed. Only those occurring while en-route on a low level mission were included in the survey, whereas accidents occurring on the airfield or during take-off or landing were not. Similarly, accidents occurring in flying operations above 1000 feet above ground level (AGL) were not included. Mission types included operational training school missions, combat ready training, and actual NATO operational flights. Where specific cause factors are available from the investigation such as engine malfunctions, bird-strikes or range richochets, these are indicated. In these cases, human factors are not significant except in the manner in which the emergency was handled. Where the cause is undetermined or obscure, the most probably cause(s) and human factors involved are allocated by the authors.

RESULTS

Of the 57 high speed, low level accidents reviewed, 28 were caused by mechanical failure, bird strike or range richochet and human factors analysis was not carried out in these cases. This is not to say that human factors did not play some part in the management of the emergency, but in many cases there was no Flight Surgeon assigned to the investigation team and human factor investigation was usually non-existant. In most of these cases, a successful ejection was carried out.

In 29 accidents, the investigating board could not determine a positive cause factor (See Table I). These investigations were studied and the following human factors were found to be present in many of the situations in varying degrees; psychological stress, fatigue, inattention, task overload, visual contrast or illusory situation, reaction time, stress of formation flying, mission completion syndrome (this will be discussed later), and pilot incapacitation. These factors were then assigned as possible primary, secondary and tertiary factors contributing to the accident. These are tabulated in Table II.

There were two fatal accidents where reduced visual contrast almost certainly caused severe disorientation leading to the accidents. One case is suspected to be incapacitation because of the autopsy findings.

DISCUSSION

Weather. There is no doubt that weather is the single most influential factor in HSLL accidents. In 13 of 29 accidents, weather was definitely a contributing factor. This is even more profound in the European environment where weather played a major part in 10 of 19 accidents. Further, if one looks at the seasons, seven of 19 European accidents occurred in the January to March time frame, and in six of these, weather was clearly a deciding factor. Typical weather conditions at the time of the accidents were low overcast or obscure ceilings with visibilities reduced to zero to one mile in snow showers. It can be fairly safely stated that fifty percent of the HSLL accidents in the European environment would not have occurred if weather conditions had been better or if the mission had not continued into deteriorating weather.

Human Factors Demonstrated

a. Visual Problems - Visual contrast or illusion are usually associated with environmental conditions. The most common variety of this problem is the "white-out" condition occurring when an expansive flat snow covered area blends with a high, light overcast and the horizon cannot be distinguished. It may also occur in other low contrast situations such as dust or haze. These conditions are ideal for the induction of disorientation which, in HSLL flight, is usually catastrophic.

Illusions also may cause errors in orientation and judgement. A sloping low cloud bank may be mistaken for the horizon. In one of our cases the height of desert sage brush in comparison to Canadian trees, combined with sloping ground conditions most likely contributed to the pilot's unawareness of his critically low altitude.

In one accident, a CF 104 on a target run collided with an RAF Canberra which was on an unrelated mission. In this case, the other aircraft was not detected until sufficient reaction time was simply unavailable. The relative closing speed between aircraft was estimated at 400 meters per second.

b. Mission Completion Syndrome - This is a psychological syndrome which causes a pilot to press on in dangerous weather or a dangerous flight profile in order to complete the mission. Many factors can make up this syndrome. They are mainly psychological factors involving self-image and peer pressures. It can be claimed that a common personality profile of pilots in general is a contributing factor - "Per Ardua Ad Astra". Of the eight accidents clearly exhibiting this phenomenon, seven involved experienced seasoned aircrew. They had considerable total flying time with little time on type and appeared to be attempting to become combat-ready in the shortest possible time. This would allow them to stand alert or take over supervisory duties such as those of Flight Commander. Some had considerable CF 104 time with the possible self-imposed notion that they should be capable of mission completion under the most adverse conditions. A reputation as one of the squadron's top bombers or gunners seems to contribute to this syndrome as does flying a mission in an international competition.

c. Stress - For the purposes of this paper, stress is defined as ... "The presence of one or more physical or psychological stressors generally leading to inattention and thence to task overload." The stressors identified in the accidents we reviewed were psychological stress, fatigue and formation flying.

Physical fatigue probably accounts for more inattention than we may suspect. In one case examined, it is highly likely that the pilot was physically fatigued severely enough to cause inattention. He had flown two missions two days previously and his wife commented that he was fatigued. The day before the accident he held a 24 hour alert. The accident occurred on the third trip the following day; a day of hectic briefings and debriefings with no evidence of between flight nourishment.

There were many forms of psychological stress detected in the human factors analysis of these accidents including a serious argument with a girlfriend, girlfriend pregnant, minor irritating malfunction of the aircraft, having had to rush to change aircraft at start-up, deteriorating weather, first flight as section or element lead and flying in an international competition.

Formation flying is in itself a stressful activity and especially so while low level. Station keeping on an inexperienced lead at low level is particularly stressful as one has a tendency to keep one eye on the altitude. One accident reviewed (a low level formation collision) can be attributed to this factor.

d. Task Overload - The task of conducting a HSLL mission is extremely demanding of a poorly trained, borderline pilot who is continually behind the aircraft. If adverse weather is then encountered or an in-flight emergency occurs, conditions become ideal for an accident.

Incapacitation. The one case attributed to pilot incapacitation was based on the fact that the autopsy findings revealed a 75 percent restriction in the right coronary artery.

The human factors listed above cannot be viewed in isolation since many of them interact to lay the groundwork for an accident. However, there are certain combinations evident in HSLL accidents which can be divided artifically into four basic patterns:

a. Type I

STRESS → INATTENTION → TASK OVERLOAD → REDUCED TIME FOR REACTION → ACCIDENT
(psychological or physical)

This seems to be the most common pattern probably accounting for 13 of the 29 accidents.

b. Type II

MISSION COMPLETION SYNDROME → TASK OVERLOAD → REDUCED TIME FOR REACTION → ACCIDENT

This pattern probably accounted for 10 of the 29 accidents.

c. Type III

VISUAL PROBLEM → REDUCED REACTION TIME → ACCIDENT
(low contrast illusion)
VISUAL PROBLEM → DISORIENTATION → REDUCED REACTION TIME

Five of our series seemed to be this type of accident, including two almost certain cases of disorientation.

d. Type IV

PILOT INCAPACITATION → ACCIDENT

One accident in our series was thought to be this type.

The advantage of splitting the accidents into these types allows each pathway to be analysed as if it were a disease process. As in most disease processes, there are signs (objective observations) and symptoms (subjective feelings) for various stages of each of these pathways. By evaluating the pathways with this approach, one can recognize areas where intervention may be possible in the interests of accident prevention. For example, recognition of dangerous stress levels with temporary removal of the affected aircrew from flight status may prevent some Type I accidents. A means of detecting reduced attention and a method of alerting the subject would also make it possible to interrupt this pathway. Inattention can also be detected by wingmen and perhaps some sort of challenge system could be developed to determine alertness.

Task overload is very difficult to recognize but it may be possible for a subject to make such a judgement before reaching the stage where his time for reaction is so short that he is fortunate to be able to eject from the situation.

The mission completion syndrome contains certain ingredients which are often recognizable; high total-time pilots in operational training or combat-ready training; high time-on-type pilots checking out new crews in adverse weather; pilots assigned to fly in international competition (especially those with previous weapons trophies) and other factors probably more readily recognized by operational aircrew.

Conditions which predispose to low visual contrast, loss of horizon or visual illusions are often recognizable and could act as a warning to pilots flying in these conditions.

CONCLUSIONS and RECOMMENDATIONS

In summary, 57 HSLL accidents were reviewed. Twenty-nine of these were found to have obscure causes and were assumed to involve human factors. In effect, these accidents are probably due to the pilot getting into a situation from which the time needed to recover is greater than the reaction time available. The question is what factors contribute to the development of this situation? We believe that the following factors are involved:

- physical and psychological stress leading to inattention;
- mission completion syndrome which drives a pilot to fly into dangerous conditions; and
- the visual problems which may result from poor weather and conditions of illusion.

It is conceded that these factors are often inter-related and difficult to separate, but for prevention purposes, they can be looked at separately. It is considered that positive action should be taken to attempt to identify and eliminate, as far as possible, these contributing human factors.

It is recommended that:-

a. The research community study the various stress factors on aircrew with a view to providing the individual aircrew and flight supervisory personnel with some means of identifying individuals who are strained to a dangerous level.

b. The research community continue to work on developing a method of detecting dangerously reduced levels of alertness or awareness in aircrew with a view to providing them with a feed-back alerting system in such circumstances.

c. Operational staffs recognize the factors which predispose to the mission completion syndrome, attempt to identify aircrew at risk, and take action to eliminate this condition.

d. The operational staffs be particularly aware of conditions predisposing to low visual contrast situations and visual illusions and to modify flying programmes accordingly when these conditions exist. In addition, attitudinal change is required. Aircrew must be convinced that it is not heroic to fly into weather which is deteriorating below safe limits.

It is appreciated that the above recommendations may be difficult to implement without compromising the effectiveness of the squadron and without destroying the "tiger" spirit in the aircrew. However, it would appear that the human factors discussed have significant accident-productng potential and efforts should be put forth in this area.

ACKNOWLEDGEMENTS

The assistance of the Directorate of Flight Safety at National Defence Headquarters, in providing information for this survey is gratefully acknowledged.

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TABLE I

Summary of Accidents Involving Human Factors

Total Accidents Where Human Factors Played the Major Role		29
Fatalities		21
Ejections:	Successful	4
	Not Successful	1
Aircraft and Aircrew Safely Recovered		3
Average Pilot Age		27 Years
Average Flying Times:	Grand Total	2184 Hours
	Time on Type	293 Hours
	Last 30 Days	23 Hours

TABLE II

Distribution of Human Factors as Accident Causes

Number of Accidents Where Human Factor was Assigned as Possible Cause Factor (n = 29).

Human Factor	Primary	Secondary	Tertiary
Visual Contrast or Illusion	7	1	4
Mission Completion Syndrome	7	4	1
Inattention	5	10	7
Task Overload	4	1	2
Psychological Stress	2	6	6
Reduced Reaction Time	1	4	7
Fatigue	1	1	2
Stress of Formation Flying	1	2	0
Pilot Incapacitation	1	0	0

DISCUSSION

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It occurred to me in reading the pre-print for this paper that possibly this business of overload might constitute a syndrome which would be recognisable by the individual. It might be possible to develop a programme similar to the USAF hypoxia training programme in which we expose aircrew members to hypoxia so that they will find out what is likely to be their own symptom pattern. I wonder if we could develop some kind of overload situation in the laboratory to which pilots could be routinely exposed so that they would be aware of their own symptoms.

CREW STATION ASSESSMENT USING THE BIOMAN MODELING SYSTEM

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ABSTRACT

Physical compatability of man and machine must be evaluated not only in terms of physical and visual interface, but also in terms of reach and clearance envelopes. Information from gross body motion simulation (i.e. movement of body segments in response to applied forces) should be used to determine and revise clearance envelopes which can significantly alter the placement of crucial controls or cockpit geometry in general. This paper demonstrates the use of the "Bioman" modeling system in evaluating the physical compatability of crew members with crew stations under emergency egress conditions and will illustrate the usefulness of this approach as both a design and evaluation criteria. Validated results from F-18 aircraft investigations, based both on ejection tower and human physiological acceptance tests, are presented to demonstrate the evaluation process of a given crew station. Furthermore, these results are contrasted against those obtained from the A-4 and F-14 and the relative propensity of direct impact injuries are discussed.

INTRODUCTION

Evaluation of a crew station must consider not only the ability of a crew member to perform his tasks but also assure that the crew station geometry does not pose a problem during emergency egress. Injuries to aircraft crews during ejection must be viewed in terms of limitations of the escape system as distinguished from inadequate crew station geometry. Injuries due to the first classification are usually a result of high G forces and inadequate restraint, whereas injuries due to the latter can be related to direct impact between body segments and the crew station interior.

Compatability of crew members with crew stations has traditionally been based on anthropomorphic, acceleration response, and task sequence data. Drawing reviews, mockups, flight simulators, prototype flight, and track and tower tests provide crucial data but suffer from the limitation of not being able to take into account the full variability in crew anthropometry and acceleration environment factors.

Mathematical modeling can be effectively used to analyze crew member-crew station compatability and has become useful as both a design and evaluation tool. Effects of initial position and inertial conditions of the occupant and aircraft can be extensively examined as they affect occupant-crew station interaction as a function of crew member biodynamic response to acceleration profiles experienced during emergency egress. Problem areas can be isolated and possible solutions effected before expensive track and tower tests are undertaken.

The "Bioman" modeling system previously described (1) was used to evaluate the proposed F-18 crew station and simulation results were compared to those obtained from track and tower tests (using instrumented dummies) as well as to physiological acceptance tests (conducted on the ejection tower) using human subjects. Results from the mathematical simulations indicated a possible foot-instrument panel contact problem that became obvious from the extensive dummy and human tests conducted. Using the various parameters established during the F-18 simulations, the A-4 and F-14 crew stations were similarly evaluated. This approach defined specific shortcomings in the F-18 crew station geometry and a redesign is presently being undertaken.

This paper describes a test procedure consisting of track and ejection tower tests, coupled with mathematical simulation, which isolated a problem area relatively early in the design of an aircraft when changes to that design are still feasible. The model, used together with supportive test data, proved to be invaluable as an evaluation tool and is presently being employed to evaluate occupant-crew station compliance in the AV-8B aircraft.

METHODOLOGY

The Cockpit Geometry Evaluation Computer Program System (CGECPS) was used to check and transform digitized crew station data (2). All relevant crew station surfaces, expressed in the design coordinate system (using buttock, water, and station lines), were transformed to a Euclidean coordinate system (x,y,z) with the origin at the design eye reference point (figure 1). On the initial evaluation computer runs, the occupant's eye midpoint (defined in the head anatomical coordinate system) was made coincident with the design eye reference point origin. The crew member's anthropometry (95th percentile subject used in sled tests conducted at the Naval Aerospace Medical Research Laboratory Detachment, New Orleans) and seating position (estimated from the seat and crew station geometry) was used to define a theoretical seat pan location

which was then checked against the existing allowable seat adjustment range (3). If within range, an ideal initial seating position was defined (i.e. crew member seated at the design eye reference point) and the simulation was ready to proceed. Exceeding the seat adjustment range defined a problem of accomodation, although this was not encountered for the crew stations analyzed.

The formulation of the occupant model (figure 2) has been previously described (4). Briefly, the upper torso was modeled using three segments (thorax, right and left shoulder elements connected by two sternoclavicular joints), whose masses and inertial properties were estimated based on Dempster's data, as were the joint locations and ranges (5). The definition of the head anatomical coordinate system and the head center of gravity location were based on Walker's analysis (6). Estimates of the neck-torso and neck-head forcing elements (spring and dashpot functions) were obtained from Becker's preliminary analysis of the data from subjects tested at the Naval Aerospace Medical Research Laboratory Detachment (7). The mass and mass moment of inertia, link lengths, C.G. locations of the limbs, and the location of the remaining joints were estimated by scaling Dempster's approximations.

The model was then exercised using the digitized F-18 crew station data, the occupant representation outlined, and a typical acceleration profile as monitored on the ejection tower at the Naval Air Development Center, Warminster, PA. The Calspan model (8) was used to provide estimates of the occupant dynamic response to this acceleration profile. In order to insure that simulation results were stable and convergent, the accuracy of the integration procedures was checked over several error levels and minimum integration step sizes for relevant variables. If the integration solutions are stable, then reducing the allowable error limits should not alter results. Outputs for various convergence tests were virtually identical and the minimum step size was never reached, indicating acceptable results. These preliminary investigations indicated a penetration of the feet into the lower instrument panel, implying a high probability of impact between the feet and the toe guard (underside of instrument panel) (figure 3).

Track tests conducted at the Naval Weapons Center, China Lake, CA., did in fact indicate a clearance problem (figure 4). All eight tests, ranging from 0 to 600 KNOTS and using 3 and 98 percentile dummies, resulted in impact between the feet and instrument panel. Since only the dummy's chest was instrumented in these tests it was impossible to accurately estimate the acceleration of the lower legs or the forces generated during impact. All 31 ejection tower tests (conducted at the Naval Air Development Center using 6 cross section percentile human subjects), employing a styrofoam mock-up of the crew station, resulted in foot-instrument panel contact of varying severity (figure 5). Contact ranged from the tip of the toe to the tibia striking the console in the region of the mid-shaft, with the more severe impacts generally occurring with the larger subjects. Again, however, since the lower legs were not instrumented no estimate of the forces generated was possible.

To adequately define the severity of the strikes in terms of accelerations, forces generated, and time of occurrence, fully instrumented dummy tower tests were undertaken In addition to the instrumented seat, the 95th percentile dummy employed had a tri-axial linear acceleration package installed in the chest cavity (figure 6). A rate gyro was rigidly mounted on the lower leg in the region of the knee to quantify the rate of pitch experienced. An additional tri-axial acceleration package was mounted on the lower leg in close proximity of the ankle pivot and the kick plate (toe guard), simulating the underside of the instrument panel, was instrumented with a strain gauge.

Since dynamic response is directly related to initial position at time of ejection, great care was taken to assure repetitive position of the dummy relative to the seat and crew station. Distances between photographic targets mounted on the seat, dummy, and simulated rudder pedals were checked before each test and adjusted when necessary (figure 7). Both the knees and the ankles were made as loose as possible to replicate a best case situation and assure reproducibility between tests. Clearly, the stiffer the joints, the more likely contact will occur. In all cases the seat was in the full down position and the angular orientation of the legs and feet, relative to the seat and crew station, were determined from the markers on the dummy. Link lengths and weights were established for the other relevant segments and used as input to the program, as were the existing initial segment angular orientations. Three tests were conducted without the toe guard installed but with the same dummy initial positions. This provided a direct comparison between the cases with and without contact. As had been the case previously, all 17 dummy tests conducted resulted in impact between the feet and toe guard.

RESULTS

In conducting the simulations and analyzing test results several changes to the original modeling effort were undertaken to make results directly comparable to work conducted by McDonnell-Douglas Aircraft Cor . (9). In addition to the Bioman graphics package, the elliptical representation (used by Calspan) of the occupant was employed. Furthermore, the crew station surfaces as digitized by McDonnell-Douglas, were utilized in the analysis so that the coordinate systems employed and crew station surfaces monitored would be directly comparable. These crew station surfaces were checked against the original data set used (figure 3) and were found to be virtually identical (although fewer surfaces were considered in this latter effort). A sample (7 cases) of the seat acceleration profiles is shown in figure 8, illustrating that the driving function of the seat-man system remained relatively unchanged from test to test. Similarly, accelerations monitored in the chest showed a high degree of reproducibility and there seemed to be no significant differences between the cases where impact occured vs those where there was no leg obstruction (figure 9). The lower

leg data however, clearly demonstrates the effect of the strike. The linear accelerations at the ankle (figure 10) showed significant differences between strike vs no strike situations, as did the angular velocities (figure 11). The loads monitored at the kick plate, as a result of the impact, were on the order of 200 Lbs and proved to be reproducible from test to test both in magnitude and time of occurrence.

Simulation results were in good agreement with test data. Monitored vs predicted values for the chest acceleration of a typical test are shown in figure 12. Comparable results were obtained for the other segments monitored. Occupant position at time of initiation of ejection and at the time when impact occurs is shown in figure 13. The effect of the strike (in simulation results) was clearly seen in segments not directly involved in the contact. Figure 14 demonstrates the effect on the thigh angular displacement. This demonstrable effect, however, cannot be quantified in terms of injury potential. Additionally, secondary effects on total human body dynamics cannot be predicted reliably since relatively small changes in force deformation properties of the toe guard, boot, or ankle characteristics have a profound effect on the time history of the lower leg and foot during and after impact occurs. Since the force deformation characteristics employed were estimates based on static tests and since the human ankle joint characteristics are not known with certainty, the range of possible resulting data was broad enough to cause concern from a safety point of view. Consequently, the position taken was that the central problem of human injury prevention is the elimination of contact and direct impact was viewed as a catastrophe to be avoided at all cost.

Using the same dummy characteristics as were employed in the F-18 simulations, the model was also exercised using digitized A-4 and F-14 crew station data. The initial positions of the dummy were modified to reflect the seat and crew station geometry existing in the respective aircraft, as were the ejection angles employed. The acceleration time histories used were those of the F-18 tower tests conducted. The relative dimensions of the respective crew stations are shown in figures 15 and 16. It will be noted that using the lower seat reference points as the origin, the F-18 crew station is smaller than the other two analyzed. Results from the simulation of A-4 and F-14 ejections are shown in figures 17 and 18 respectively. Both cases resulted in no strikes, although in the case of the A-4 the clearance provided is marginal. Slight changes in initial occupant position or acceleration of the man-seat system could result in contact between the feet and the instrument panel.

DISCUSSION

The data presented clearly indicates that toe/foot strikes appear to be a very high probability event regardless of aviator size or seat adjustment. Anthropometric limitations therefore will not solve the problem. Furthermore, tibia strikes are possible and in larger aviators more probable. Despite no simulated strikes in the cases of the A-4 and F-14 aircraft, there have been strikes in operational use. This is primarily due to the fact that during operational ejection the aircraft need not be in a stable situation but might have large angular and linear acceleration components. Furthermore, the idealized occupant restraint considered in the simulations probably does not exist in the operational environment. Consequently, the results indicate that the F-18 simulation is underpredictive.

From the tower tests conducted, additional areas of concern were isolated. With the large subjects, seat fully down, and with maximum forward throw adjustment in the rudder pedals, the thigh is raised above the thigh support. At the time of ejection, therefore, there can be thigh slap on the seat bucket which might cause femur injury. In the simulations, the thigh was supported at all times and the differences between hit and no hit situations shown in figure 14 are due to the changed force deformation properties at the thigh- seat bucket interface. If the seat is raised so that the thighs come in contact with the thigh support, the helmeted head (for a large occupant) may be raised so high that the aviator might have to compromise his seating position to stay within the cockpit, thus pre-loading the vertebrae and increasing the probability of vertebral fracture on ejection.

As a result of the data presented, the problems isolated were deemed significant enough to convene a medical panel to analyze the data in terms of injury potential. This medical panel, consisting of representatives from the Naval Aerospace Medical Research Laboratory Detachment, Naval Air Systems Command, Naval Materiel Command, and Naval Air Development Center, considered the problem severe enough to make the present crew station configuration unacceptable.

Although a basic redesign of the crew station might have to be undertaken, some possible engineering concepts involving only the toe board and rudder pedals were analyzed. A "Dynamic Kick Plate", deployed from under the instrument panel was installed and tested on the ejection tower. The rather crude mock-up of this concept consisted of an aluminum plate hinged to the underside of the instrument panel (figure 19) and coming in contact with the toe during ejection initiation. Theoretically the manner of deployment should be such as to maintain constant contact between the kick plate and the foot throughout the entire time period while the foot is under the instrument panel. The mock-up deployment was simplified through the use of a counter weighted aluminum rod. As the foot moved away from the rudder pedal, the kick plate pivoted downward with the rod being forced into the wedge created by the toe guard and kick plate. This arrangement imparted a slight angular acceleration component to the lower leg and foot but did guide the toes past the point of impact.

Film analysis indicated, however, that contact between the toes and the kick plate was not maintained throughout the entire course of the run. Since the displacement of the legs exceeded the plate deployment rate, which was a function of gravity (the rate at which the bar increases the toe guard-kick plate angle was determined by a weight pulling the rod into the wedge), motion of the kick plate tended to lag behind that of

the foot. Spring, hydraulic or ballistic deployment would obviously improve results but since this was considered a feasibility test, the aforementioned improvements were not undertaken. Nevertheless, results from this pilot study proved to be extremely encouraging. Figure 20 shows the data obtained from the three tests conducted. The solid lines indicate the contact forces monitored on the right foot with the kick plate installed, while the dashed lines demonstrate the data from the left foot where impact was allowed (no dynamic kick plate). Since the kick plate was initially preloaded, the forces in the early stages go negative because the instrumentation was zeroed out at the time of initiation (i.e. since the toe exerts a slight force on the kick plate, the fulcrum created by the rod produces a negative component at the strain gauges). Since the foot was not maintained in constant contact with the kick plate some spikes in the data are evident (solid lines) but their magnitude (approx. 50 Lbs) are clearly much lower than those monitored on the unprotected leg (approx. 200 Lbs). It must be remembered that these feasibility tests addressed only the foot impact problem and leave the accomodation questions previously discussed unresolved.

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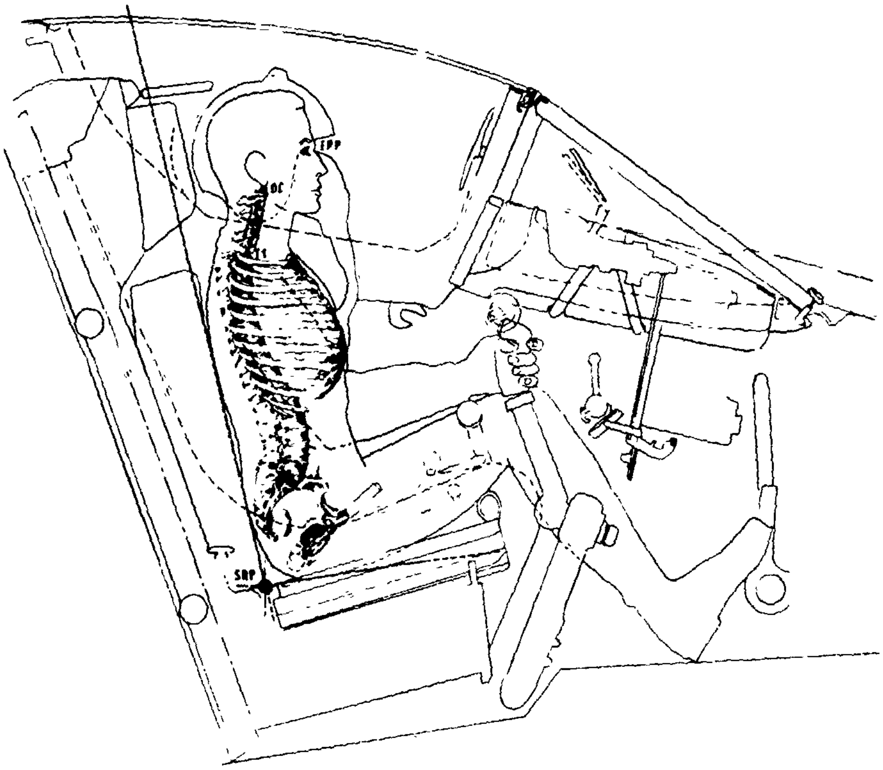

Fig.1 Occupant seated at the design eye reference point

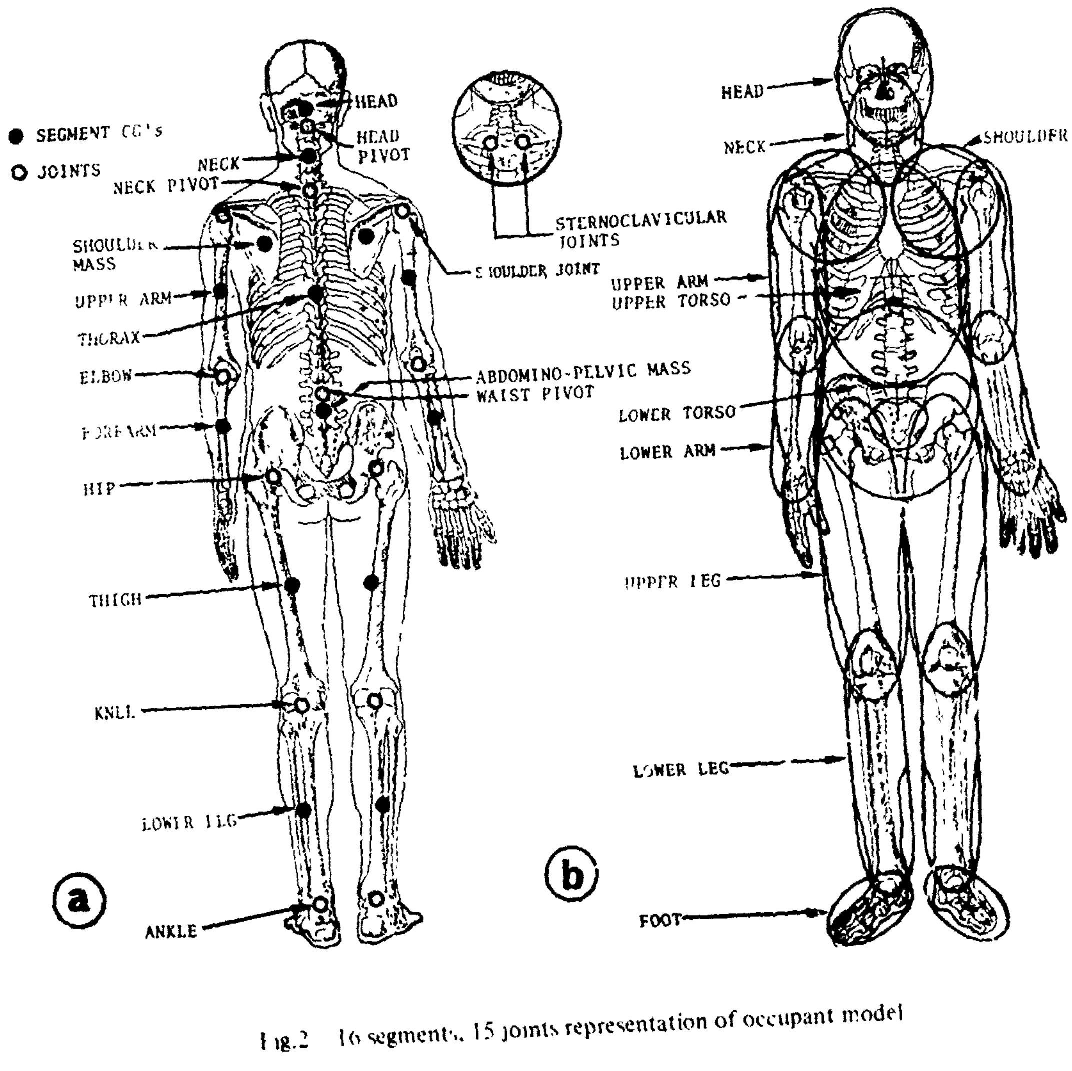

Fig.2 16 segments, 15 joints representation of occupant model

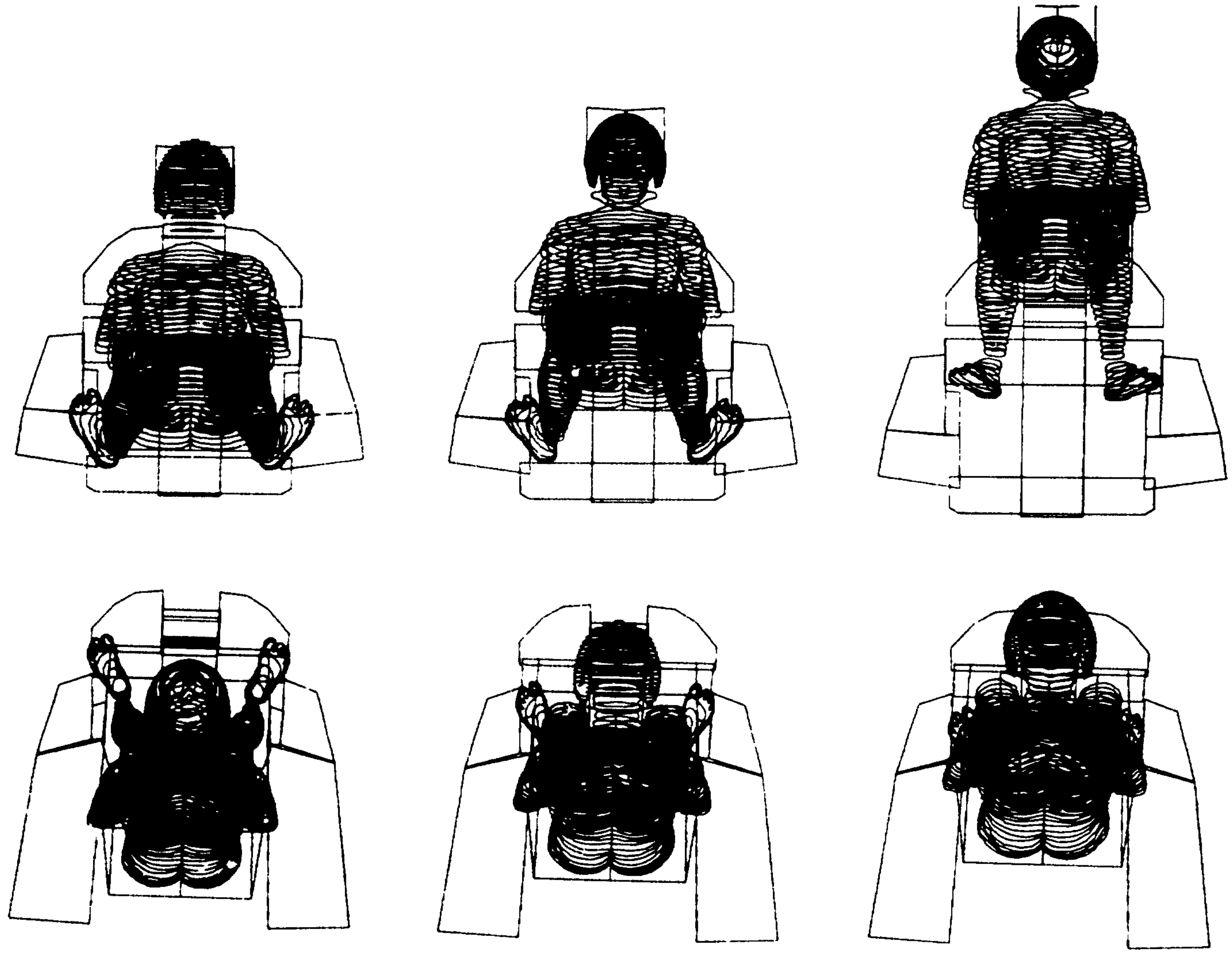

Fig.3 F-18 ejection simulation
Top half – view from rudder pedals looking up
Bottom half – view from shoulders looking down

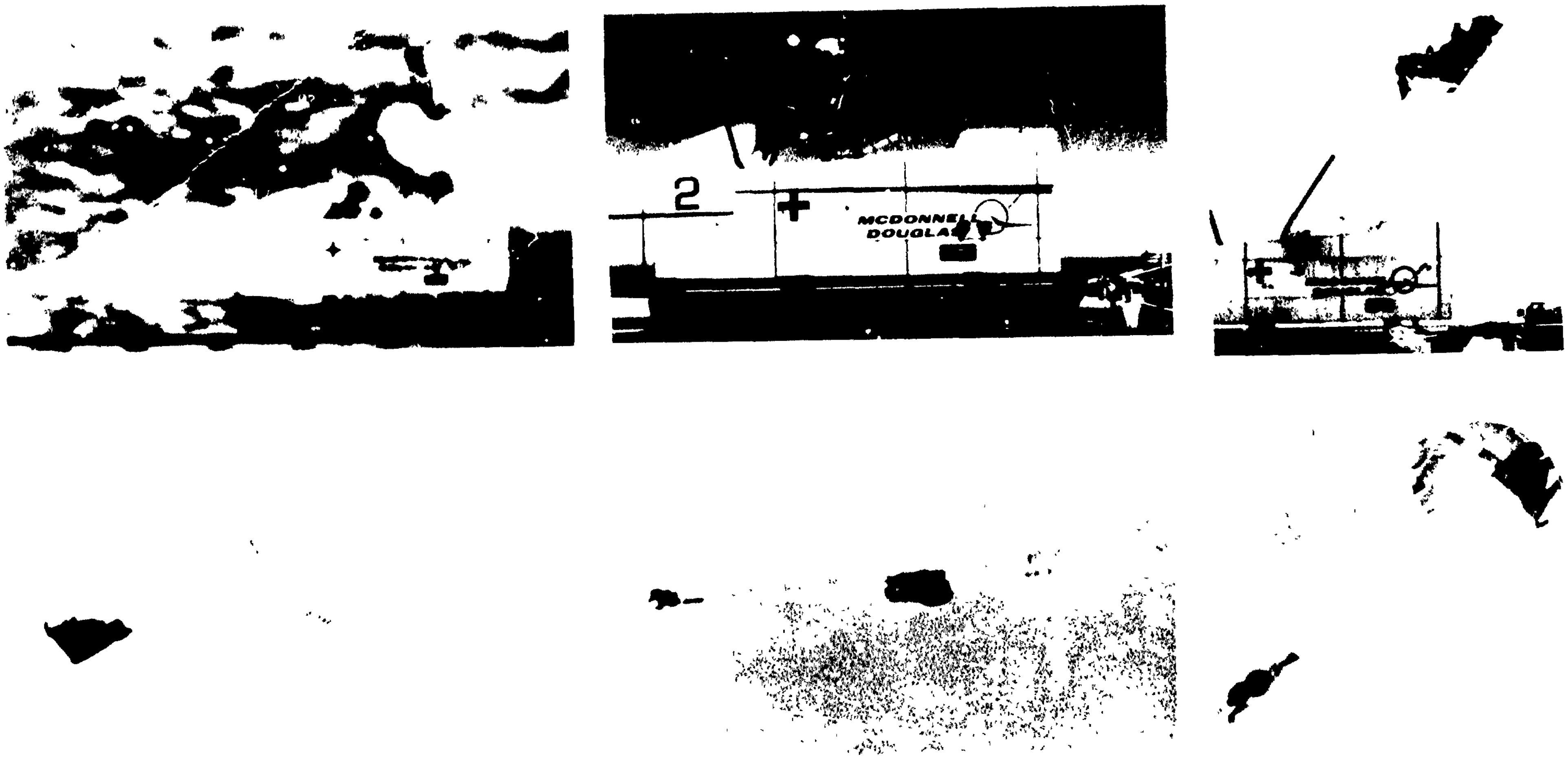

Fig 4 Composite of high speed track test for F-18 ejection seat

Fig 5 Human physiological acceptance test at NADC tower facility

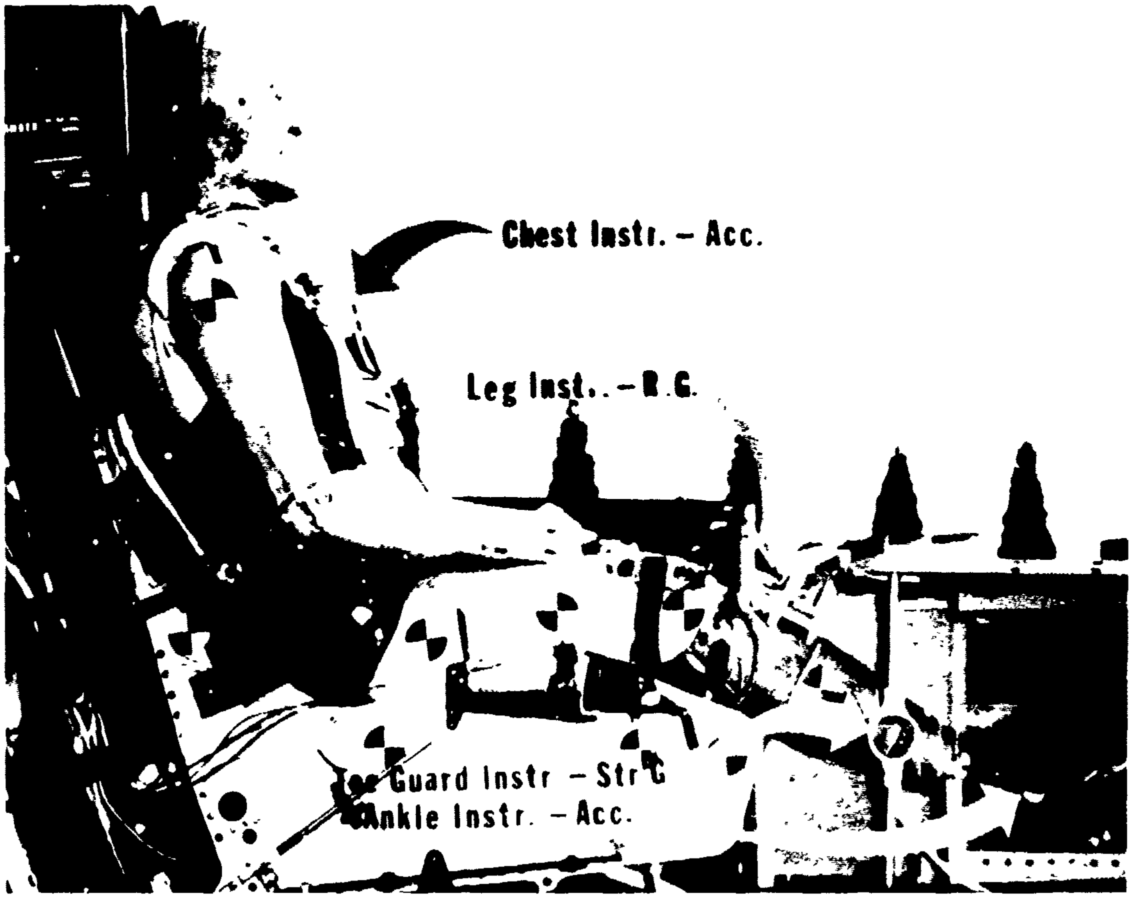

Fig.6 Instrumentation location on dummy tower tests

Fig.7 Initial position definition of dummy relative to seat and crew station

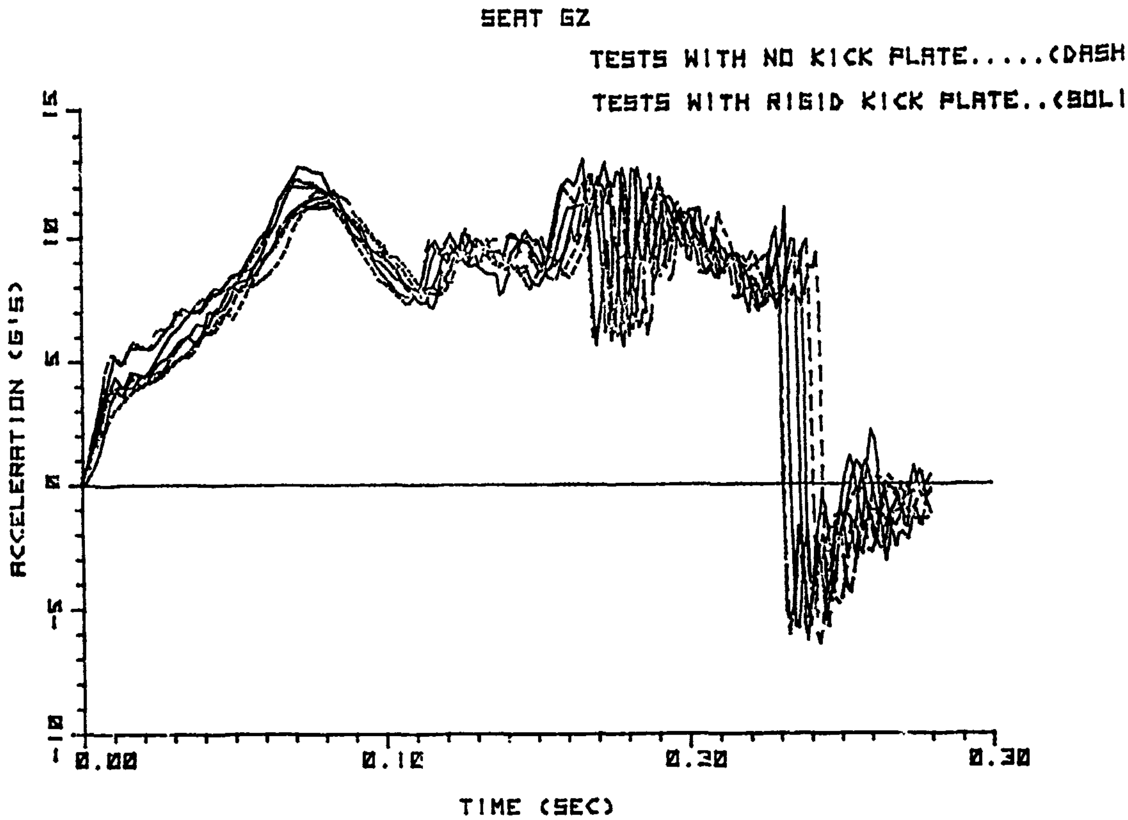

Fig.8 Monitored seat acceleration time histories

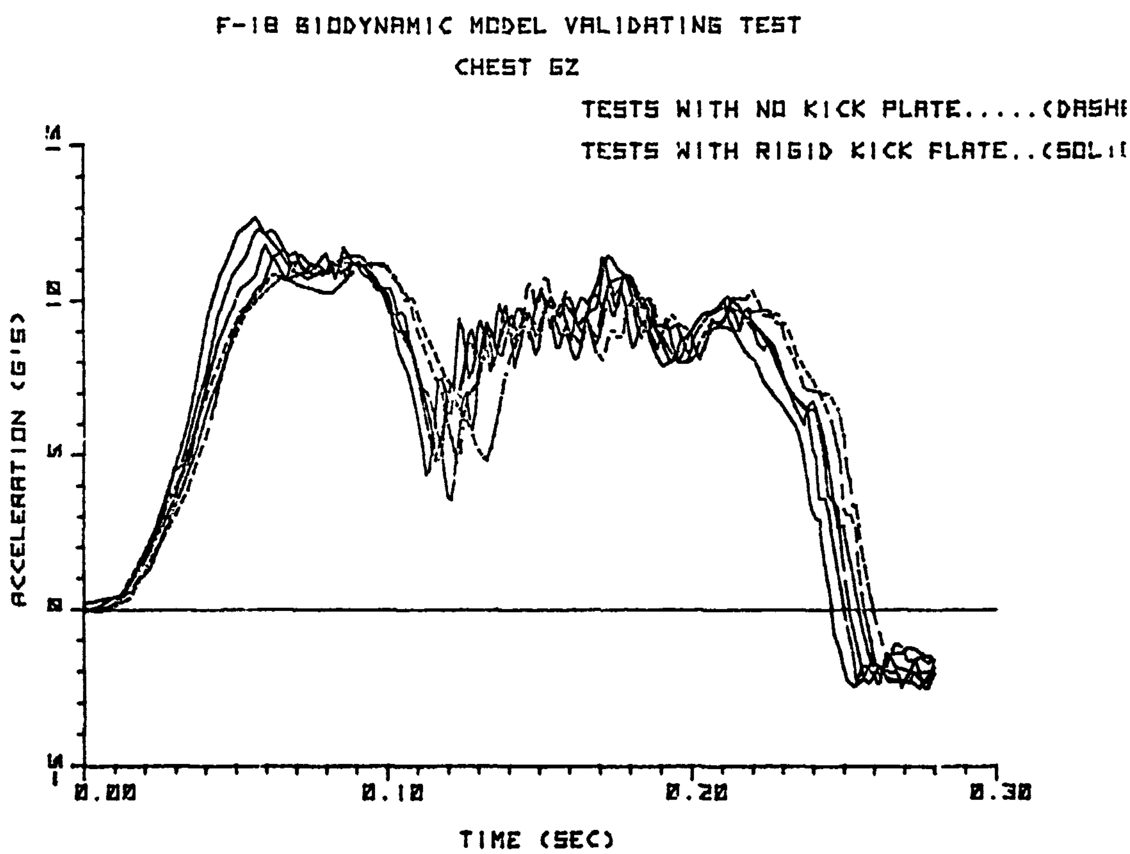

Fig.9 Monitored chest acceleration time histories

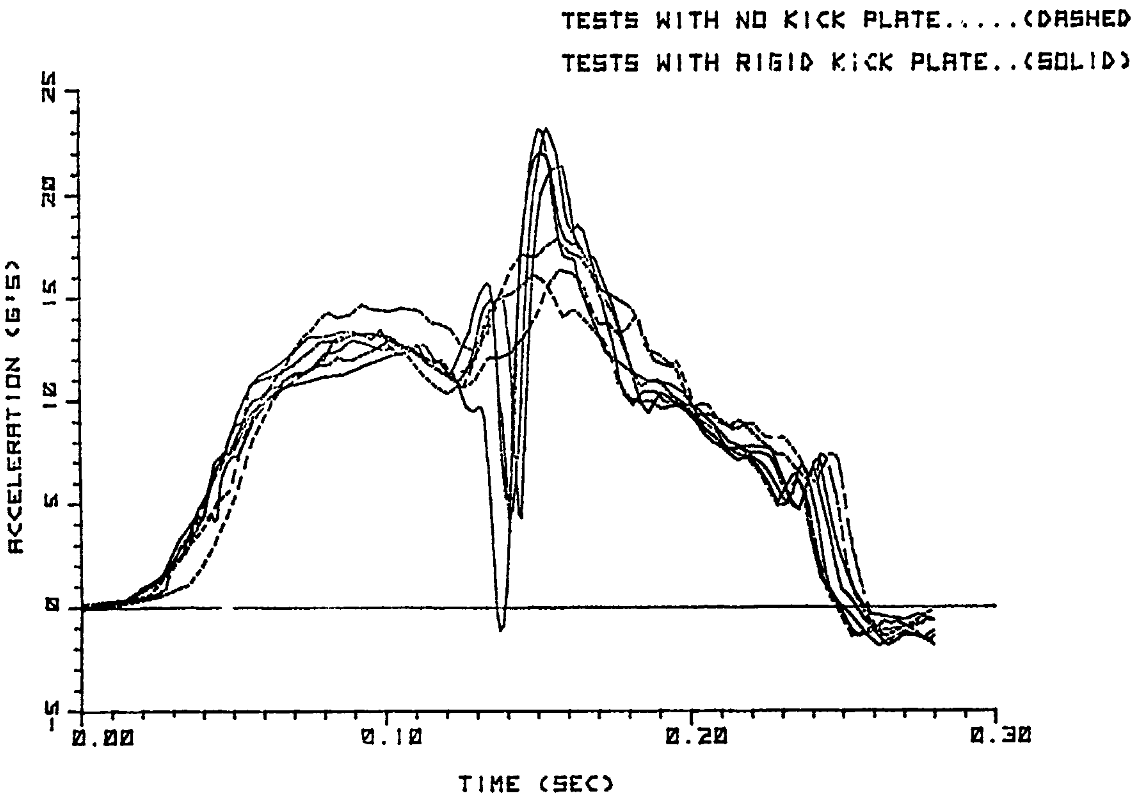

Fig.10 Monitored lower leg linear (Gz) acceleration

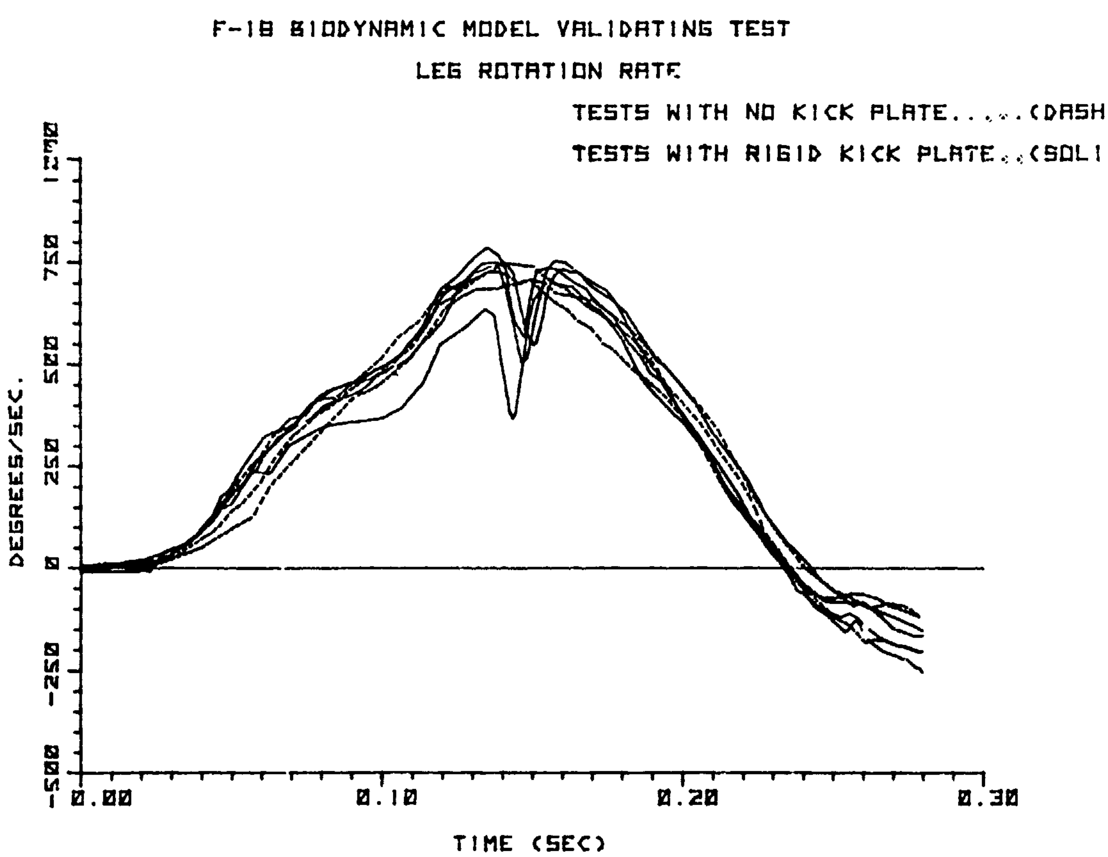

Fig.11 Monitored lower leg angular velocity (pitch)

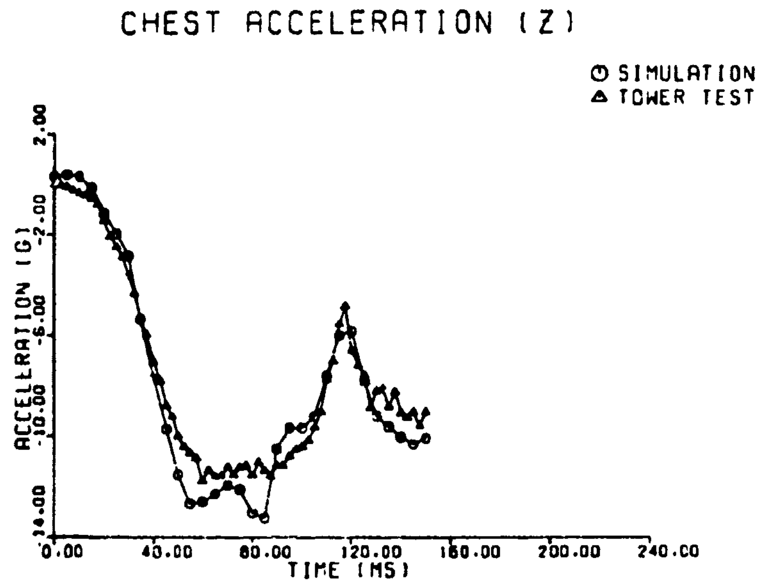

Fig.12 Monitored vs predicted chest linear acceleration

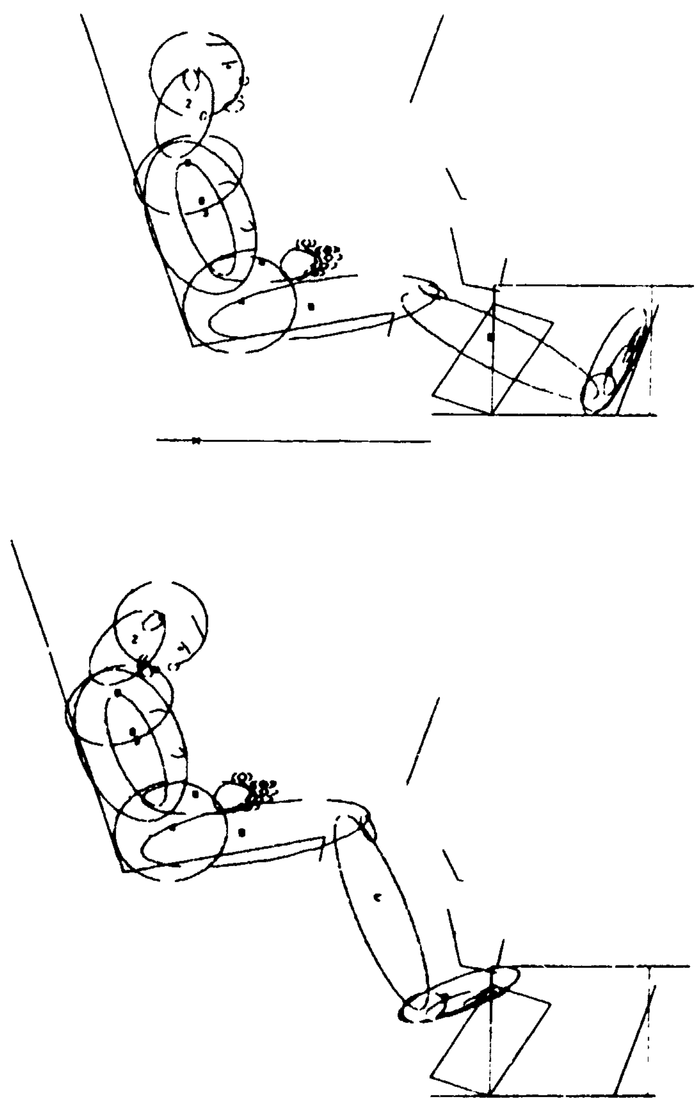

Fig.13 Elliptical representation of F-18 ejection

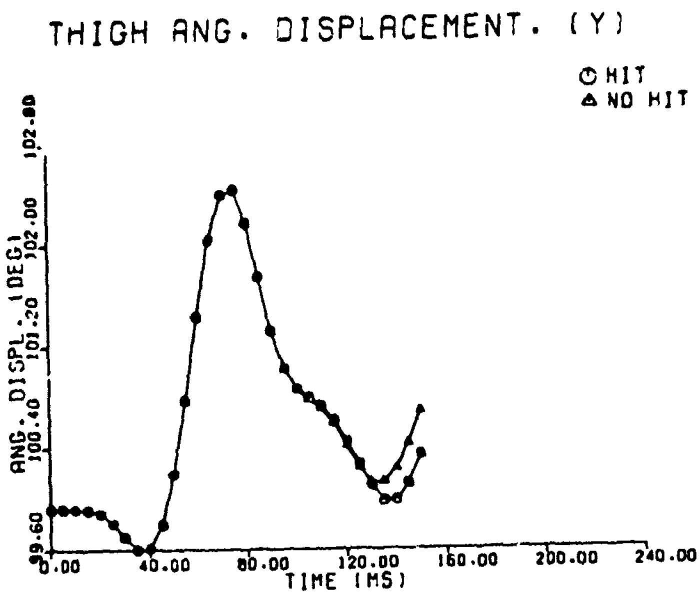

Fig.14 Thigh angular displacement (pitch)

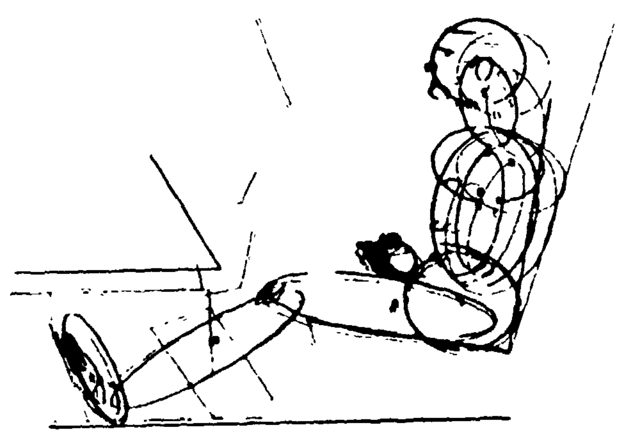

Fig.15 A-4 vs F-18 relative crew station dimensions

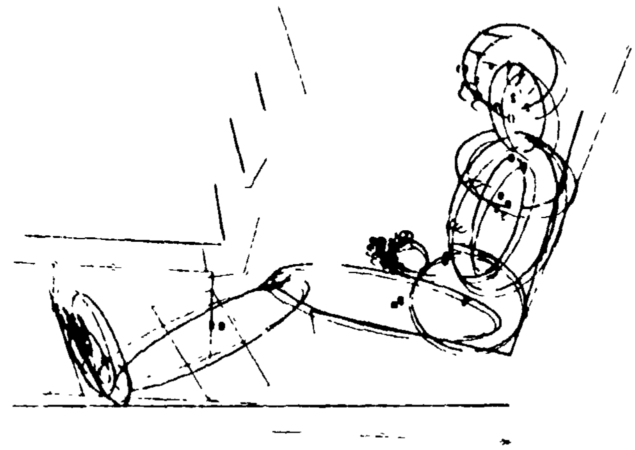

Fig.16 F-14 vs F-18 relative crew station dimensions

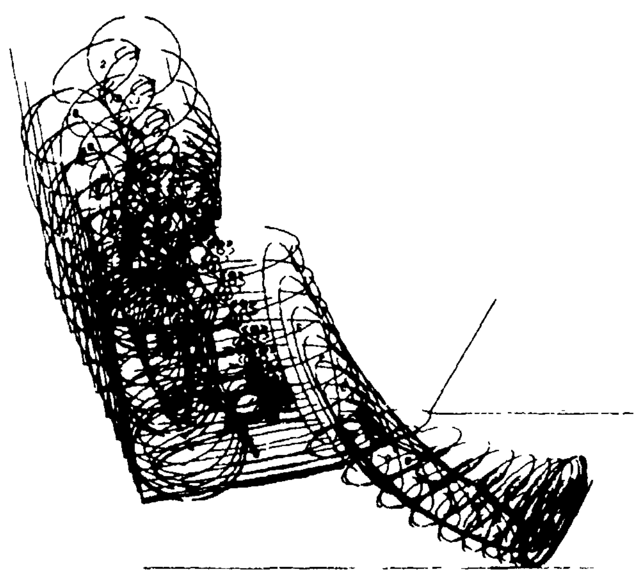

Fig 17 Composite of ejection sequence from A-4 aircraft

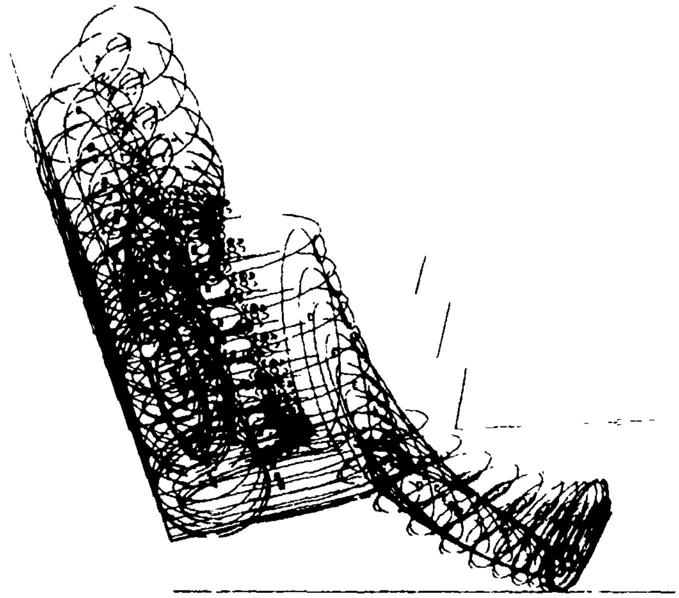

Fig.18 Composite of ejection sequence from F-14 aircraft

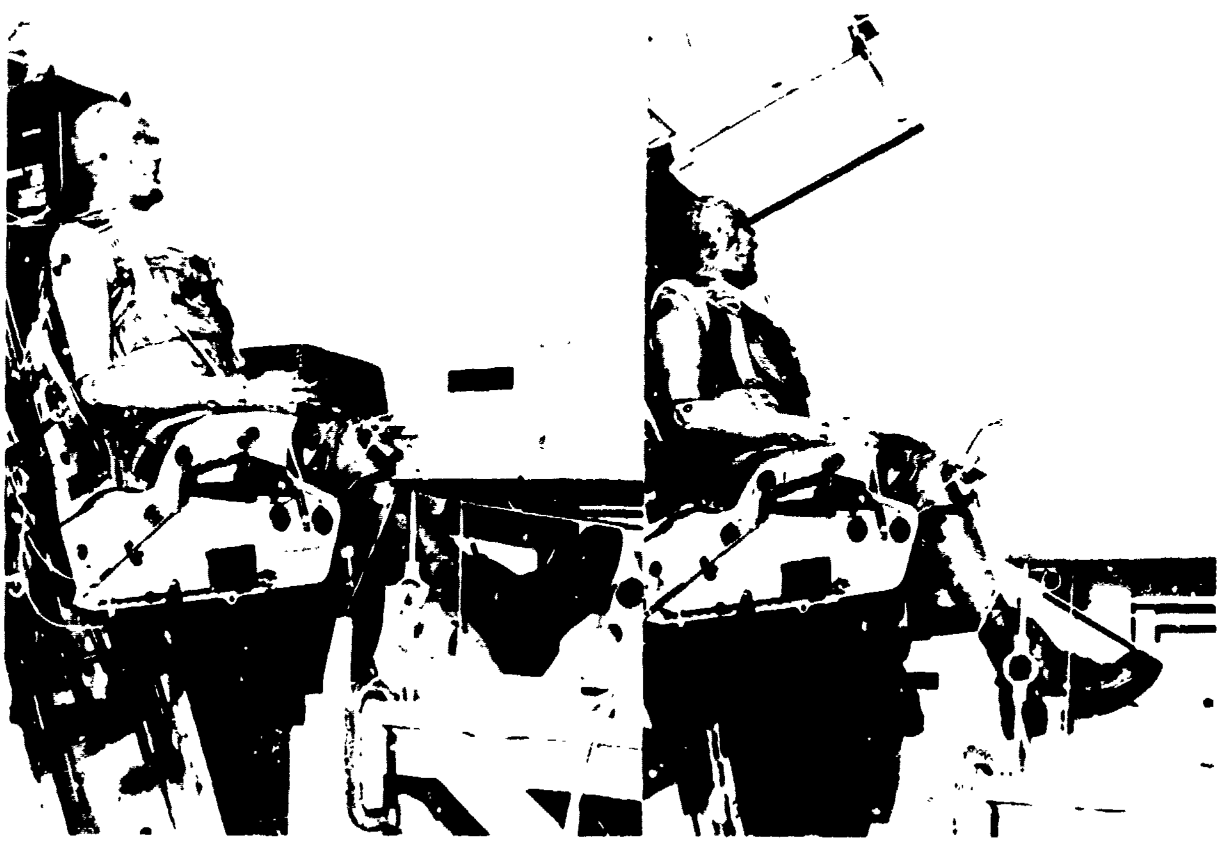

Fig.19 Dynamic kick plate deployment during ejection

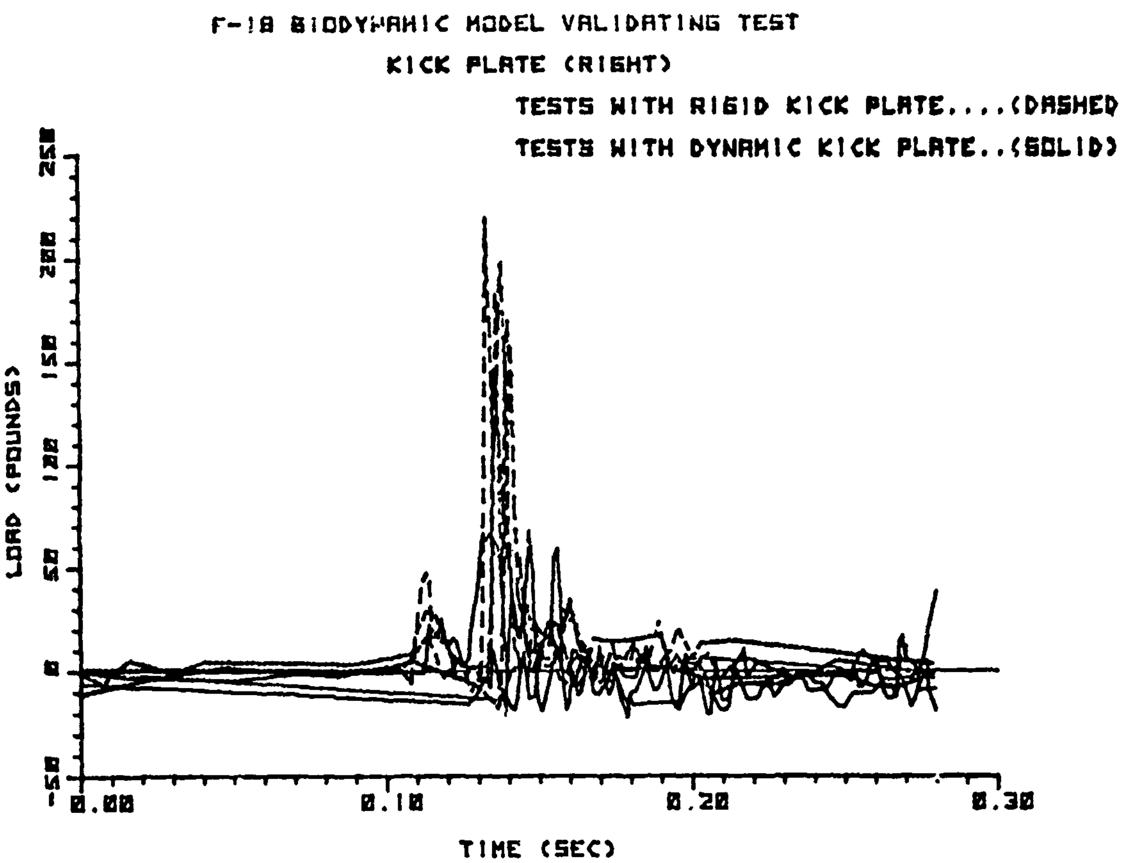

Fig.20 Monitored kick plate forces during ejection

NAVAL AVIATION WATER SURVIVAL PROGRAM

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The very nature of naval aviation requires that the majority of operation flights be conducted overwater. The missions vary from operations in the immediate vicinity of aircraft carriers and shore bases to single aircraft flights hundreds of miles from the nearest land. Each situation presents unique problems in terms of required survival equipment and length of time to rescue. Major revisions to the Naval Aviation Water Survival Program are presently underway. The Training curricula are being standarized and water survival instructors will be extensively trained to conduct the training. Aviation Life Support Systems are being modified to provide automatic life preserver inflation and parachute divestment. New water training devices are being procured and training will be conducted in the devices with the same configuration of life support equipment that the aircrewmembers fly with.

Because of the equipment, unique operational requirements and differences in life support, three aircraft classifications will be presented· Tactical Jet, Patrol/Transport and Helicopter.

(1) TACTICAL JET: Slide (1) depicts a typically configured jet aircrewmen. In addition to the usual protective flight clothing, each individual is equipped with an inflatable life preserver and a one man inflatable raft contained in the rigid seat kit. The seat kit also contains an emergency supply of oxygen. The oxygen systems for tactical jet aircraft are water tight and are required to function properly at a depth of 16 ft. for a minimum of three minutes. During the ejection sequence the aircraft oxygen supply hose is separated and the emergency oxygen supply is activated. In this aircraft community the oxygen mask must be worn continuously from take off to landing. In the U.S. Navy there have been over 40 reported cases of underwater breathing with this system.

The amount of man-mounted survival equipment has been reduced in the past few years by removal of the survival vest. The current survival equipment philosophy is to provide life support equipment to sustain the survivor for 24 hours. With the removal of the survival vest, pockets were sewn directly to the integrated restraint and parachute harness, as can be seen in Slide (3). This minimal amount of equipment is obviously not sufficient for long term survival. Naval Safety Center records reveal that 91% of the aircrewmembers recovered are rescued in one hour or less. This reduction in man-mounted equipment allows more freedom of movement and less encumbrance in the cockpit as a trade-off to less equipment available to the survivor. The survival vest contains slightly more survival equipment and can be worn at the individual crewmembers discretion. The seat survival kit contains and emergency radio beacon, a small survival kit, signal flares, mirror and sea dye marker.

Ejection from a jet aircraft can injure the aircrewmember and prohibit use of any of the survival equipment. The majority of ejections occur at such low altitude that no time is available to prepare for water entry. The classical example of this is an unsuccessful catapult launch from or recovery on an aircraft carrier. In this instance the ejectee has only seconds after the decision to eject until he is in the water. The heavy bulky configuration of life support equipment also hampers survival efforts. The Naval Weapons Station, Yorktown, Va. published a report in December 1978 that described the effect of immersed life support equipment. According to that report the life support equipment of a fully configured jet crewmember with the rigid seat survival kit unopened and still attached to the man exerts a negative buoyant of 14 2 pounds on the man. This additional weight combined with the bulk of the equipment and the rigid seat survival kit makes swimming almost impossible. The survival problems encountered after water entry are shown in Slide (5).

As can be seen in this slide, from the period 1971 to 1977 56 of 213 individuals experienced parachute entanglement. Ten of these individuals were not only entangled but were pulled down, to varying degrees, by the parachute. Of all the survival equipment carried the shroud line cutter has been the piece of equipment most often used in the past few years. The navy has recently contracted for several parachute disentanglement trainers. With this device the trainee is pulled from a simulated cockpit and swung over the water. There are two modes of operation for the device. In the low altitude mode the student is allowed to drop part way to the water stopped abruptly to simulate a 3-6G parachute opening shock, and allowed to drop in the water with no time to prepare for entry. In the high altitude mode the student is allowed time to inflate the life preserver and perform other pre-landing maneuvers. The parachute canopy is approximately 14 ft. in diameter. After it has collapsed over the student he must then free himself from the parachute and shroud lines, swim free of the parachute and prepare for rescue. The first of these trainers will be delivered to Pensacola, Florida with additional devices being procured for other water training sites. An automatic parachute divestment systems is currently being developed.

This system is integrated directly into the parachute attachment hardware (Koch Fitting) and requires total immersion into salt water to actuate. This system is expected to be operational in 1980.

With the life preserver fully inflated, retention of all the survival equipment and even and some minor parachute entanglement poses no serious threat to drowning because the head is supported well above water level. However, in many cases there is not sufficient time to inflate the life preserver prior to water entry. The crewmember must then remain afloat, divest the parachute, and inflate the life preserver while wearing wet gloves. The present trend in water survival training is to conduct drills in the water with the same configuration of life support equipment that is utilized in the aircraft. Experience to date has revealed that a fully equipped tactical jet crewmember with the life preserver uninflated can remain afloat for less than two minutes after water entry. Failure to actuate both sides of the life preserver has resulted in several drownings. Typically the individual will inflate the side of the dominant hand and not be able to locate or actuate the other. The effect of one half inflation is graphically depicted in the next two slides. As can be seen in Slide (12), during the time period 1973 to November 1977 a total of 188 individuals obtained full inflation of the life preserver in the water and even with retention of the survival kit and/or parachute only one fatality occurred. With only one half inflation there were 11 drownings of 40 ejectees reported in the same time period. One half inflation provides approximately 30-35 pounds of positive buoyancy. Since the survival equipment with the seat pan attached and unopened creates 14.2 pounds of negative buoyancy it causes the individual to float at slightly below chin level in still waters with one half inflation. The neck is not supported and with any wave action water will break over the head causing the survivor to swallow and aspirate water, further degrading his physical condition.

Two life preserver modifications are currently in progress to aid with inflation. One is the replacement of the pull toggles for the preserver. The present toggles are small rounded plastic pieces that are stitched closely to the casing of the life preserver. The replacement actuation mechanisms will be beaded handles attached to the ends of the life preserver casing. This configuration is very similar to one used for several years in the united kingdom. An automatic inflation device is also being procured. This device actuates when totally immersed in water, fresh or salt, within three seconds. The automatic inflator will be utilized only in tactical jet aircraft since escape from a ditched aircraft would be seriously affected with the life preserver inflated. These devices are expected to be operational in late 1979 or early 1980.

(2) PATROL/TRANSPORT: The floatation garment used in this community is the same one utilized in tactical jets with a different attachment scheme to the body. The survival vest is also utilized by the patrol aircraft crewmembers. Since the seat survival kit is not utilized in these communities, the survival equipment and single man raft are not available. Multi-man raft are utilized in patrol aircraft and are stowed inside the aircraft. These rafts must be pushed or carried out of the aircraft after ditching. Transport aircrewmembers do not routinely wear life preservers, but stow then aboard the aircraft. Some of the transport aircraft have externally mounted multi-man rafts that are expelled after water impact. Duration of survival is the most important consideration for this community

(3) HELICOPTERS: Helicopters are not equipped with parachutes and the aircrewmen must rely on water landings for escape A few helicopters are equipped with fuselage floatation bags, but most are not. Because of the weight distribution in helicopters the center of gravity is high on the aircraft and after impact they tend to roll inverted and sink rapidly. Approximately one half of all helicopter water accident survivors reported that they were forced to escape from submerged or partially submerged aircraft. There have been 306 fatalities in Navy and Marine Corps helicopters from 1969 to November 1977. A total of 29 individuals were known to have been drowned and an additional 58 were lost at sea. Many of those lost at sea were probably drowned, but could not be verified. The most prevelant causes of difficulty reported in escape from helicopters are: In-rushing water, confusion/panic/disorientation, hampered by equipment, difficulty reaching the hatches and darkness.

Training in underwater egress has proven to be a definite factor in helicopter survivability for both aircrewmembers and passengers. Between January 1969 and February 1975 a total of 424 individuals were placed in a situation of escaping from an aircraft in the water. Of those who had been trained in underwater egress, 92% of them survived, while only 79% of the untrained individuals survived. Underwater egress has been taught for several years in the "dilber dunker" device. This device does not simulate a helicopter in configuration or sinking characteristics, but does instill confidence in one's ability to egress underwater. The device simply slides down the tracks, impacts the water and inverts The training of helicopter crews in underwater egress is being improved by the development of a helicopter ditching trainer. This device is configured much the same as a helicopter interior. Panels can be moved and escape hatches changed to simulate specific aircraft configurations.

This device can accommodate up to 6 trainees with each cycle. The students enter the device from the platform above the pool and attach themselves to the seat with the appropriate lap belt/shoulder harness. The device is then lowered into the water at a rate of up to 10 FPS. After water impact the trainer floods and sinks at a rate of up to 1 FPS. The device can be rolled in either direction up to 180 degrees. The students are instructed to remain seated until the device stops and then to disconnect from the seat and move to an exit port and swim free of the trainer. This trainer requires a dedicated training pool 24 ft. by 34 ft. by 15 ft. in depth. The only operational device is presently located in Pensacola, Florida and an additional four or five devices will be placed at other Navy and Marine Corps activities. Four training cycles are performed with each student, two with

unobstructed vision and two while wearing darkly colored goggles to simulate night escape.

In February 1979 the Chief of Naval Operations approved an operational requirement to improve helicopter aircrew survivability. The major elements of that program are: crash impact energy attenuation, fuel fire suppression, fuselage floatation/sink rate retardation, emergency egress and improved life support equipment. If a floatation or sink retardation system can be placed on all helicopters the requirement for emergency underwater egress would be minimized. One new navy helicopter is being procured with floatation devices and many in-service aircraft can be retrofitted, but some helicopters in inventory cannot accept the weight penalty.

The Naval Aviation School Command at Pensacola, Florida has been designated as the Aviation Training Model Manager for water survival training. In this capacity that command is developing standardized training curricula. Water survival instructors will be sent to Pensacola for a period of approximately four weeks of training in order to provide qualified swimmers/instructors and standardized training. Almost all initial aircrewmember water training will be conducted at Pensacola. The training will include basic swim skills, device utilization and open water training in the Bay. Refresher training is required every three years in the swimming pools and every five years in open water. Efforts are presently underway to initiate overwater parasail training as part of the five year open water syllabus.

For global operations aircrewmembers must be prepared for all weather and water conditions. In late 1978 a navy operational requirement for anti-exposure protection was approved. The criteria established for immersion hypothermia protection are: the crewmember must be able to accomplish the mission, protection in 45°F water for two hours with body core temperature of not less than 95°F, the system must be able to be graduated to afford protection in 32°F water for two hours with a core temperature of not less than 95°F. As an interim measure the navy has selected the British Ventile suit as the primary anti-exposure garment, and a divers wet suit as an alternative.

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HIGH SPEED LOW LEVEL FLIGHT SURVIVAL ON EJECTION

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The aim of this paper in the short time available is to show the history of past work conducted by our Company in association with other Research Establishments on High Speed Low Level Ejection. The paper itself will be split into three phases, Past Experience, Current Day Practice and finally A Look Into the Future.

As aeroplanes get faster and faster one hears glib talk of tree top level flight at speeds of 800 knots and above using terrain following radar. When one considers that the dynamic pressure exerted on the human body at speeds of 600 knots are in the region of 1,280 lbs. per square foot it is easy to realize that the man leaving the aircraft can be critically injured by the dynamic forces applied to him and also inevitably is liable to be deeply shocked by the experience.

In 1962 the TSR2(Tactical Reconnaissance Aircraft) was designed to travel at speeds of up to 800 knots at tree top level. At that time Martin-Baker recognized that a completely new escape system was required to meet the problems associated with this type of flight. Bearing in mind that the average pilot would spend all his life sitting in the seat and never using it as an actual escape vehicle then the primary consideration was excellent restraint for the body so that the pilot would be secured firmly into his seat thus reducing fatigue caused by constant turbulence. In order to achieve this object a ratchet system was used where the crewmember could tighten his harness by means of a ratchet which meant that he was snugged back into the seat. The seat also produced amongst other notable firsts : Head Restraint, Arm Restraint and of course Martin-Baker's Leg Restraint System. It was quite an achievement that Sir James Martin should have recognised in these early days the requirement for such excellent restraint systems to allow the ejectee to survive under highspeed bale out. The evidence, which I shall present later, will be based on experience in both the American Vietnamese situation and the Yom Kippur War. A slide of the seat is shown here and as can be seen a special helmet, which included head restraint, was under development for the programme.

The TSR2 was unfortunately cancelled during one of our Government's many 'save money by cutting defence' campaigns. Thus the actual ejection seat never came into service, however, one point that should be made here is that that particular seat weighed very nearly 300 lbs.

During the 1960's further developments took place, however, nothing as sophisticated as the TSR2 seat was introduced to Service. Leg Restraint Systems were improved however it was impossible to get anybody to show interest in Arm Restraint.

During the late 1960's and early 1970's considerable operational use was made of our ejection seats in action during the Vietnamese situation and Yom Kippur war. Both these conflicts provided us with valuable data regarding the changes likely to take place under operational ejections as opposed to normal peace time ejections. As may well be expected the speeds at which ejections took place increased. I believe that the main reason for this was the fact that aircraft were flying lower and faster than ever before and at the same time having little warning before they were hit by surface to air missiles. The slides that I show here firstly show the combat versus operational ejection altitudes and also combat versus operational ejection speeds. It is notable that the operational non combat speeds show their largest percentage well below 250 knots with a diminishing number of ejections up to 500 knots. In contrast recovered combat data and data obtained from prisoners of war in the Vietnamese situation show that the speed curve rises sharply. As we would expect as the speed rises so does the injury rate and I show here on the next slide evidence taken from the Vietnamese situation showing the percentage of survivors sustaining a major injury. As you notice the major problem is one of limb flail and so on this next slide I show the incidences of major flail injury versus ejection speed and again as can be seen the percentage of flail injury rises sharply as the speed rises This is hardly surprising as when one looks at the dynamic air pressure versus air speed which I discussed earlier in the paper and we see that the dynamic air pressure rises sharply as the speed rises and indeed it varies approximately with the square of the indicated air speed.

The other major problem of course is one of lack of time. As aircraft fly faster and faster and lower and lower using terrain following systems the vexed problem of altitude gets worse and worse.

My next slide shows the summary of the ejections of those using Martin-Baker seats during 1977 and the major causes for fatality. As you can see the lack of time and altitude is the major cause of fatalities, other areas obviously require investigation and we have done so in some depth especially to try and avoid ejecting aircrew suffering the unnecessary fate of drowning. In this particular year of 1977 my next slide addresses the question of altitude. As you can see more than 43% of all ejections where the height was reported, started below 500 ft. and the table shows the altitude bands into which they fell. It is also notable that in the Yom Kippur War 26% of ejections were made at speeds of 400 knots or greater. This is higher than the average and at these speeds limb flailing is liable to occur. 4% of all ejections were made at a speed of 600 knots or more. The major injury which occurred during the Yom Kippur War was again mainly associated with flail. So now coming back to the subject that I was first addressing : where does this lead us with regard to high speed low level flight? It shows us that the major improvement that we can make in ejection systems is to ensure that the man is properly restrained and also given the best chance of survival by making the system work as rapidly as possible without causing injury and thus impairing his chance of ultimate survival.

Early trial work with the MRCA Tornado produced some fairly spectacular results as this short snip of cine film that I show here indicates. The shot you see is taken from the pod camera of the MRCA Tornado sled and shows first of all the canopy being jettisoned followed by the sequenced ejection of two seats. The seats themselves functioned correctly, however, you will note that the aircrew equipment assemblies virtually disintegrate as they meet the windblast at a speed of 625 knots. This leads me to my next major point which is that the total aircrew protective system must be integrated and tested fully to ensure its integrity under high windblast situations we must ensure that the helmet, lifepreserver, arm restraint and leg restraint are capable of accepting ejections at speeds of up to 650 to 700 knots. In my opinion the only method of satisfactorily testing these pieces of equipment is to put them on the dummies during the ejection test shots. Valuable information can be obtained from wind tunnels but it is usually unidirectional and does not allow for yaw in the seat or indeed any other changes in geometry.

Now let us consider those areas that will be most beneficial in saving the life of a man who ejects at high speed and low altitude. We must assume that the man who ejects at any speed above 450 knots is going to be winded and suffering from shock to a greater or lesser degree. We therefore need to make his survival as automated as possible. To this end our current state of the art provides an ejection seat on which the last physical act that the man needs to make is to pull the handle to set the sequence system, canopy jettison and subsequent ejection of the seats in motion. As he exits the aircraft he is protected from limb flail and arm flail and we have ensured that his helmet will stay on his head having been tested at extremely high speeds, up to 700 knots, in a wind tunnel and is fitted with a polycarbonate visor which will withstand the blast. As the man comes out of the aircraft an automatic IFF system is tripped which shows that an ejection has taken place on all the radar screens which are currently painting the aircraft. As the man separates from the seat the automatically inflated liferaft and automatically inflated life preserver are armed ready for operation on water entry and the personal locator beacon is switched on to transmit. As the man comes down on his parachute he falls into the sea and both liferaft and life preserver inflate and at the same time the man is supported in the water by his life preserver. The beacon is of course continuously transmitting. Obviously if the man is unconscious he will not have been able to remove his oxygen mask from his face and to this end we have provided a self-closing valve in the lower end of the man's oxygen hose and an anti-suffocation valve in the mask and this will enable the unconscious pilot, whose head is being supported above the water by his life preserver, to continue to breathe. We have not at the present time included automatic release of the parachute as this is not a device that is currently accepted by air staffs most pilots fearing a malfunction due to some mechanical mishap. However, we have conducted trials which show that the parachute sinking beneath the sea will not act as a drogue and drag the man under for a period of at least 25 minutes in a rough sea. Even beyond that time it is unlikely to do so. These systems are already in service today and provide the man with an increased chance of survival especially under adverse conditions. However, I am sure that most of the people in this audience are well aware that although the opportunity exists to install such equipment on all aircraft very few Air Forces or Navies indeed have taken the comprehensive package and I can say that at the present time only the Tornado has taken the complete overall protection approach. The US Navy are currently working on a man safe design of equivalent capabilities to the Tornado but plan to automatically disconnect the parachute at water entry. Again this seems to be a programme that has had very low priority and therefore I sometimes wonder what are the chances of persuading today's requirements divisions to accept the designs of tomorrow when we currently cannot get our existing equipment up to a reasonable standard.

However, to look at the more cheerful side; where are we heading for in the future? One area which bears considerable investigation is the reclining seat which is now being looked at for aircraft of the future. This seat improves the mans tolerance to 'G' and also decreases the fatigue factor and in fact I know the Chairman of our current panel session Wing Commander David Glaister has in fact done centrifuge runs in a supernated seat of around 10G. Now we must make this supernated seat suitable for ejection and we have therefore been working on this aspect over the last few months and I show here a film of a mock-up employing proven principles that incorporate into a design giving the reclined seat effect. It is noticeable that during this short snip of film that you can see that whilst the seat is being reclined or returned to the upright position then little or no change is taking place in the tension in the harness or the geometry of the eye position, the head remaining in the almost identical position to that from which it starts. The only area in which the geometry is changing are the rudder pedals and I believe that it should not be beyond the engineering ingenuity of most people to design this simple feature into a reclining seat aircraft. Again we are up against the problem of time and here again we have managed to reduce the retraction time of the seat pan with the man in it to .23 sec. and hope shortly to reduce this further to .15 sec. once we have the facilities for doing so. This will mean that if the aircraft has a jettisonable canopy then during the time that the canopy is clearing the aircraft the seat can be carrying out that retracting movement.

There are other projects such as the USN sponsored Maximum Escape Performance Seat (MEPS) which seeks the cold of space and directs a verniered rocket to project the seat upward away from the ground; capsules which are expensive and require frequent expensive modification as weights within the cockpits change - and many other embryo ideas.

I can think of no better way of closing than to quote the words of a distinguished U.S. Navy Admiral, Vice Admiral Frederick Turner who stated recently :

"We have seats and ejection systems that literally hurl the man out into the darkness in all different directions, unstabilized, limbs akimbo, neck snapping and even though he might be extricated from the falling machine and thrown into the air, he may be incapacitated when free of the aircraft because of injury ..... He needs some mechanical or technical assistance to reduce the shock, keep his senses going and give him some little time. He needs some automatic systems to divest him of emcumbering parachutes, gear about his face and the like, when he is thrown into the sea."

Well gentlemen we in the U.K. have made some progress in this area but we can go no further without the acceptance by Air Forces and Navies of such systems.

MINIMIZING THE SEQUENCED DELAY TIME FOR ESCAPE FROM HIGH-SPEED, LOW-LEVEL FLIGHT PROFILES

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The time delay that occurs between the actuation of an escape system and the actual initiation of the ejection catapult acceleration to separate the crew from an aircraft is one of the critical factors in the design of escape systems for high-speed low-level (HSLL) flight conditions. This delay may preclude what could otherwise be a successful escape from certain HSLL profiles. The purpose of this paper is to examine the significance of current operational delay times and describe techniques to minimize the delays. Operational through-the-canopy ejection data are presented to assess the risk of injury incurred in eliminating the delay time altogether. Experimental data from tests with human volunteers are presented to demonstrate the potential for significantly reducing the time required for upper torso retraction. Finally, the implications of available aeromedical evidence are evaluated in the definition of the most promising approaches to minimize the time required for a HSLL escape sequence.

INTRODUCTION

The problem of providing a successful means of escape from a disabled aircraft is quite severe when the aircraft is operating in the high-speed low-level (HSLL) flight regime. Many contemporary escape systems are capable of providing survivable ejection from a variety of flight profiles, including an aircraft parked on the ramp or one flying at high speed and high altitude. However, when high speed and low altitude are confronted in combination, these same systems may function poorly. This result derives primarily from considerations of available time. Low altitudes and high speeds imply the potential for ground contact before the escape system can complete its function. The circumstances are particularly crucial in the face of other adverse factors such as terrain variations, high sink rates, or unstable flight conditions.

A timely decision to eject is particularly important in the HSLL regime. However, once that decision has been made (either by the pilot or by an automatic system) the crewmember must usually remain in the aircraft unwillingly while the pre-ejection sequence takes place. This period typically involves approximately 300 milliseconds, during which the canopy may be jettisoned and the upper torso and/or extremities pre-positioned for ejection. When these activities are completed, the seated crewmember is accelerated out of the aircraft. It must be emphasized that this 300 milliseconds is added to variable delays associated with recognition of the emergency, decision making, attempts at corrective action (if any), and actuation of the escape system.(1) The interaction of the various escape factors is diagrammed in Figure 1. Several of the factors will be discussed in greater detail later in this paper.

In a high performance aircraft, 300 milliseconds can be a significant period of time depending upon situational variables such as the nature of the aircraft emergency and the component of aircraft closing velocity with an obstruction. If the aircraft is breaking up or departing from stable flight, much can be said for exiting the aircraft promptly, even at high altitude. When the aircraft is approaching an obstruction, successful ejection must generally occur well before aircraft impact since the ejected mass must clear the aircraft, decelerate, and accomplish parachute deployment before its residual velocity carries it into the obstruction as well. As an example of the significance of a 300 millisecond delay, it can be seen that an aircraft moving at a velocity of 400 knots will travel approximately 200 feet in 300 milliseconds. At 600 knots, the distance covered will be approximately 300 feet. The critical parameter is not the scalar speed, however, but the vector component of velocity in the direction of the most serious obstruction. In the majority of cases, the aircraft vector velocity is such that a significant velocity component is parallel to the obstruction. In order for the 300 millisecond delay to be significant in determining successful ejection, the trajectory must be such that, with the delay, an otherwise survivable ejection is compromised. One simplified way to assess the importance of this parameter may be seen in Figure 2. The maximum recoverable dive angles are plotted as a function of speed for various altitudes, with and without the 300 millisecond delay. These figures are computed from published performance data for the A-10 ejection seat in the high speed mode at 0^{o} roll.(2) Each shaded area represents the range of constant dive angles at that altitude for which the 300 millisecond delay is decisive. For each altitude, dive angles above the shaded area are all non-recoverable ejections. Dive angles below the shaded area are all recoverable ejections, with or without the delay. At 300 feet, it can be seen that the dive angles for which the delay is decisive are limited to a 3.5^{o} to 5.5^{o} band, depending on the aircraft speed. For example, at 450 knots, the delay is decisive only for constant dive angles between 15^{o} and 18.5^{o}. On either side of that band in this simplified case, the outcome is independent of the presence or absence of a 300 millisecond delay. As altitude increases, the delay at first becomes more significant, as at 700 feet in which the critical band ranges from 8.5^{o} to 20^{o} depending on the speed. For example, at 250 knots, the delay is decisive for constant dive angles between 63^{o} and 83^{o}. Here, however, the dive angles involved are much steeper, and consequently less often encountered. As ejection altitude is increased still more, the presence or absence of the delay eventually becomes completely inconsequential with respect to terrain impact avoidance.

Similar families of curves can be generated for other flight profiles, incorporating various roll angles, roll rates, or more complex trajectories such as a parabolic curve with increasing dive angle. Such analyses will continue to demonstrate that the 300 millisecond delay is decisive in only a small percentage of potential ejection trajectories. This remains true since the delay is significantly smaller than the time from ejection initiation to parachute opening. During this time, the ejected mass

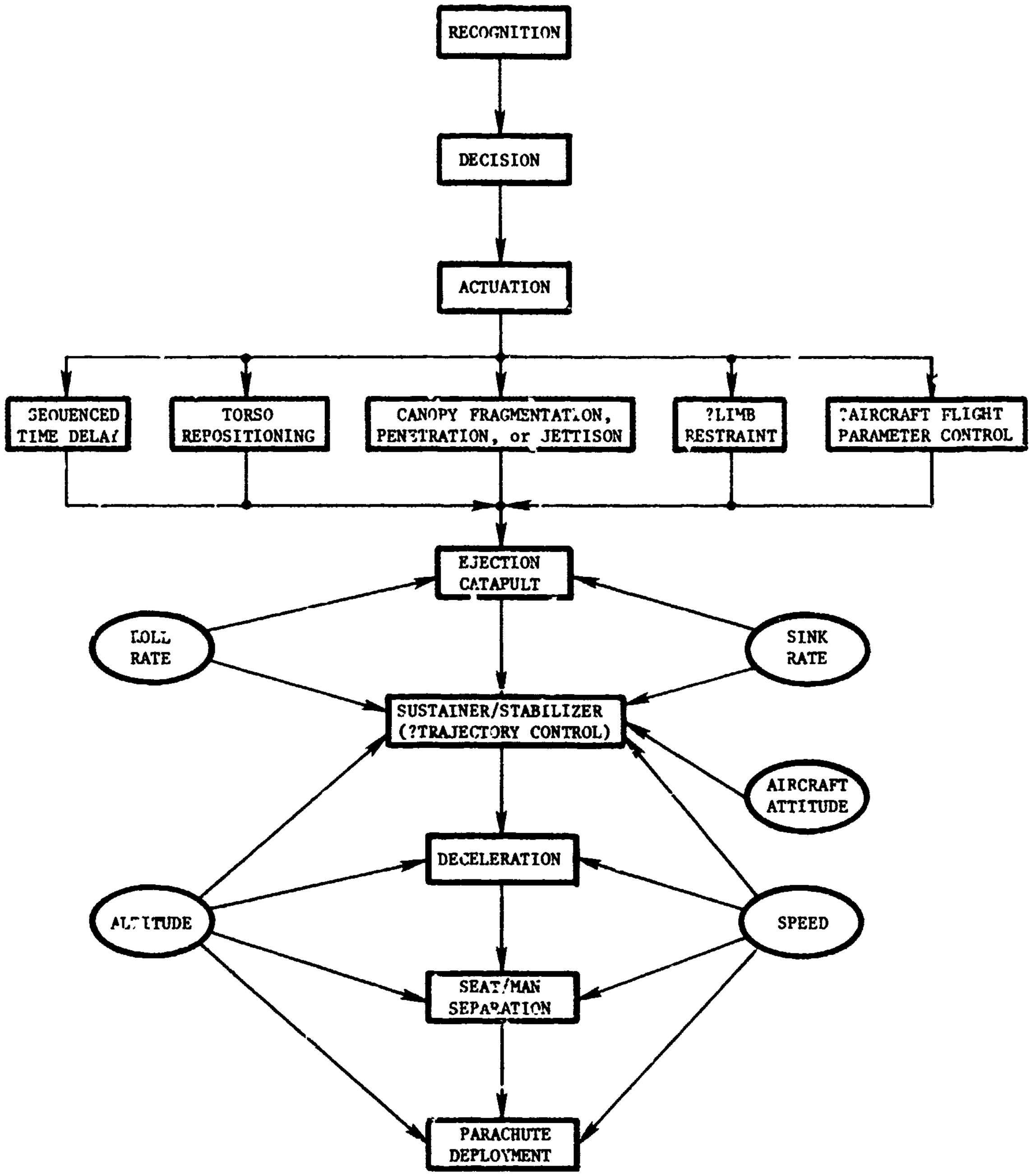


Figure 1. EJECTION SEQUENCE FLOW CHART

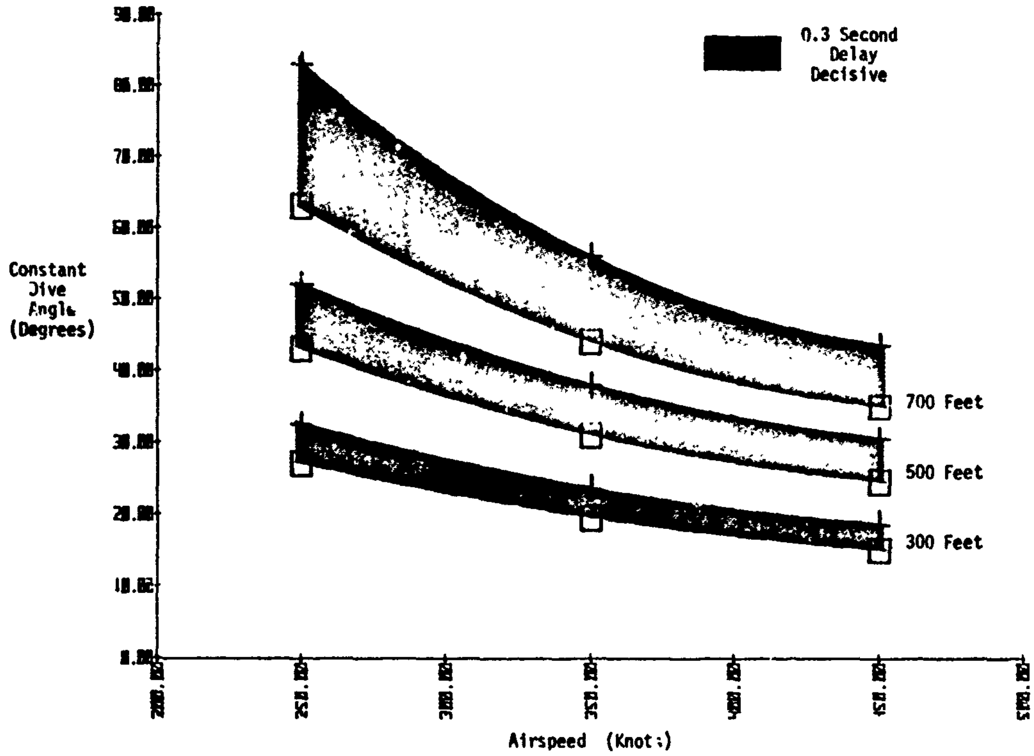


Figure 2. TRAJECTORIES FOR WHICH 0.3 SECOND DELAY IS DECISIVE

may travel great distances in the direction of the aircraft flight path at ejection. This is precisely why techniques which delay parachute opening in order to produce complex trajectory changes may be deleterious in some cases. The difficulty is most easily seen with trajectories in which the closing velocity with the ground is greater than can be overcome by the available ejection seat thrust and in which the initial ejection direction is already favorable, which is usually the case.

Therefore, when we consider a problem such as the 300 millisecond delay which is expected to be decisive in only a small minority of potential ejection scenarios, we must take great care to avoid instituting a solution to the problem which would compromise safe performance of the escape system in the majority of situations.

TECHNIQUES FOR FASTER EJECTION

The sequenced delay problem could be attacked by reducing the effects of the delay, reducing the delay, or by a combination of both. The potential for reducing the effects of the delay will be briefly examined first. The techniques will include more rapid escape system actuation and aircraft trajectory modifications before and after escape system actuation.

In spite of the significance of the short time intervals of the ejection sequence, it remains true that the most significant delays occur prior to ejection sequence initiation. These delays occur as a result of the time required to recognize an emergency, decide on a course of action, and initiate escape. Furthermore, the course of action may include one or more attempts at corrective efforts which involve further reaction times to accomplish these efforts and assess results. The importance of a timely decision to eject is frequently stressed to aircrew members, and appropriately so. However, significant benefits may be realized by automatic systems to facilitate this function, particularly in the HSLL flight environment. An example of this approach is the pitch-up maneuver that is automatically engaged when failure is detected in a terrain following autopilot. This maneuver allows the crewmember additional time for assessment and, if necessary, escape initiation. More sophisticated sensing of aircraft flight parameters and terrain clearance could allow automatic initiation of emergency aircraft maneuvers, short of actual ejection, even when the aircraft is being manually flown. The philosophy for such systems would require special attention to limit their actuation to situations in which a clear departure from controlled flight has occurred. Optional manual initiation could be employed. Their function could be to deploy speedbrakes and seek to gain favorable altitude and flight path with respect to terrain. Actual ejection initiation could be left to the pilot or accomplished automatically in clearly irrecoverable departures from controlled flight. Such systems may allow safe recovery from otherwise impossible situations. Their use seems more reasonable under HSLL flight conditions when it is recalled from Figure 1 that a 19° dive angle leads to an irrecoverable ejection from 300 feet at 450 knots, even without sequenced delay.

If consideration is limited to manual escape initiation, the aircraft may still be designed to automatically sense critical flight profiles, display warnings, and allow escape system actuation from the crewmember's flying position with minimum motion consistent with protection against inadvertent operation.

The basic intention of this paper will now be served by pursuing an examination of techniques to reduce the 300 millisecond sequenced delay time. Since the delay is normally used to jettison the canopy and accomplish upper torso repositioning, reducing the delay must affect the performance of both functions. Three basic approaches suggest themselves:

1. Decrease canopy removal time;
   Decrease torso repositioning time.

2. Eliminate canopy removal;
   Decrease torso repositioning time.

3. Eliminate canopy removal;
   Eliminate torso repositioning.

A fourth permutation (decrease canopy removal time, eliminate torso repositioning) can be discarded if it is assumed that torso repositioning is desirable and that it can be accomplished at least as rapidly as a faster canopy removal. An additional assumption is that limb restraint must not necessarily be complete before firing of the ejection catapult.

Strictly from time considerations, the third alternative appears preferable since it allows immediate ejection initiation with system actuation. However, based on conclusions from the previous discussion, such a "solution" would only be preferable if the improvements to be realized outweighed any costs to be incurred in terms of ejection morbidity and mortality. The improvements to be realized cannot be clearly quantified without a knowledge of the population statistics of the ejection parameters to be encountered in future HSLL operations. From the previous analysis, however, it could reasonably be expected that the delay will be critical in a minority of cases. On the other hand, it is intuitively desirable to increase the safe ejection envelope, by no matter how small an amount, with the expectation that it will help sooner or later. The basic question is then related to the possible costs incurred in eliminating upper torso retraction and ejecting immediately through the canopy.

THROUGH-THE-CANOPY INJURY DATA

Operational data are available to assess the experience with several through-the-canopy (TTC) ejection systems in which upper torso retraction was not performed. These data were analyzed in order to assess the potential risk associated with a proposed modification to a low-level aircraft which would introduce a TTC system as the primary escape mode. Figure 3 demonstrates a comparison of the results of 16 pairs of ejections from the United States Navy A-6 aircraft.(3) The pairs were formed by utilizing 16 available canopy jettison ejections and obtaining a best match for altitude and speed at ejection from among 114 ejections through-the-canopy. The adequacy of the matching can be seen in Table 1. The summary in Figure 3 indicates significantly increased injury rates for lacerations in the TTC data ($p = 0.1$). Spinal fractures appear to be increased in the TTC data but are not found to be significant at the 90% confidence level for this small sample. A similar match was performed using 22 non-fatal TTC ejections from the United States Navy A7 aircraft (3). These were matched with A7 canopy jettison data from among 152 ejections. The matched parameters are shown in Table 2 and the injury comparison in Figure 4. In this case, the TTC ejections showed a significantly increased rate of spinal fractures ($p = 0.1$) and lacerations ($p = 0.05$).

These data are particularly significant when the ejection equipment is taken into account. In both comparisons the TTC system had milder ejection seat thrust profiles than did the canopy jettison systems. This should tend to produce fewer spinal injuries in the TTC experience but, in fact, the reverse was true.

A further interesting finding in these data was the distribution of spinal fractures observed. A total of 394 ejections were examined from a variety of United States Navy aircraft, including 224 TTC ejections. The resulting spinal fractures are summarized in Figure 5.(3) The bimodal distribution is in contradistinction to the large sample of United States Air Force spinal fracture data shown in Figure 6. (3) This data is modal about a peak which occurs in the lower thoracic-upper lumbar region. The mid-thoracic peak in some data samples has been previously reported elsewhere, (4) but in this sample was found to derive largely from the TTC systems. A similar mid-thoracic peak has been claimed for Air Force F/FB-111 and F-4 ejection data.(4,5) Surprisely, available data from 64 United States Air Force inadvertent TTC ejections did not demonstrate the mid-thoracic peak (Figure 7).(3)

The operational injury data does not delineate cause and effect mechanisms; however, it does indicate that a cost in terms of morbidity and mortality may be incurred when the sequenced delay time is eliminated altogether. The cost may well be out of proportion to the small benefit to be gained from eliminating the delay. This cost may derive from ejecting through the canopy or from failing to retract the upper torso or from a combination of the two. If the source of spinal injury is related to ejecting through the canopy, the question remains as to the mechanism of injury production. Downward loading through the head or shoulders may be implicated. Alternatively, temporary retardation of the seat, as it forces its way through canopy material, could produce a surge in the acceleration of the seat and, therefore, the force transmitted to the spine through the seat pan. A third possibility is flexion of the spine during catapult firing in the absence of windblast force until clearing the canopy. This mechanism is based on the supposition that the head and torso of the ejectee are benefited by the restraining force of aerodynamic pressure acting on the ejectee after canopy jettisoning. Newer approaches to TTC ejection incorporate various designs of canopy weakening or canopy fragmenting pyrotechnics using mild detonating cord (MDC). Whatever the postulated mechanism of injury, it would appear that active dispersal of the canopy by a pyrotechnic system would minimize the likelihood of the canopy being a contributor if a clear path for the seat/man combination could be provided.

Without a clear definition of cause and effect in the observed injury data, it is unlikely that a test approach could be proposed which would prospectively assure that a given TTC system would not produce similar injuries. The best that can be reasonably expected would be to design a system which avoids the imposition of forces that appear most likely to be implicated and await an operational assessment.

Figure 3
A6 MATCHED PAIR ANALYSIS

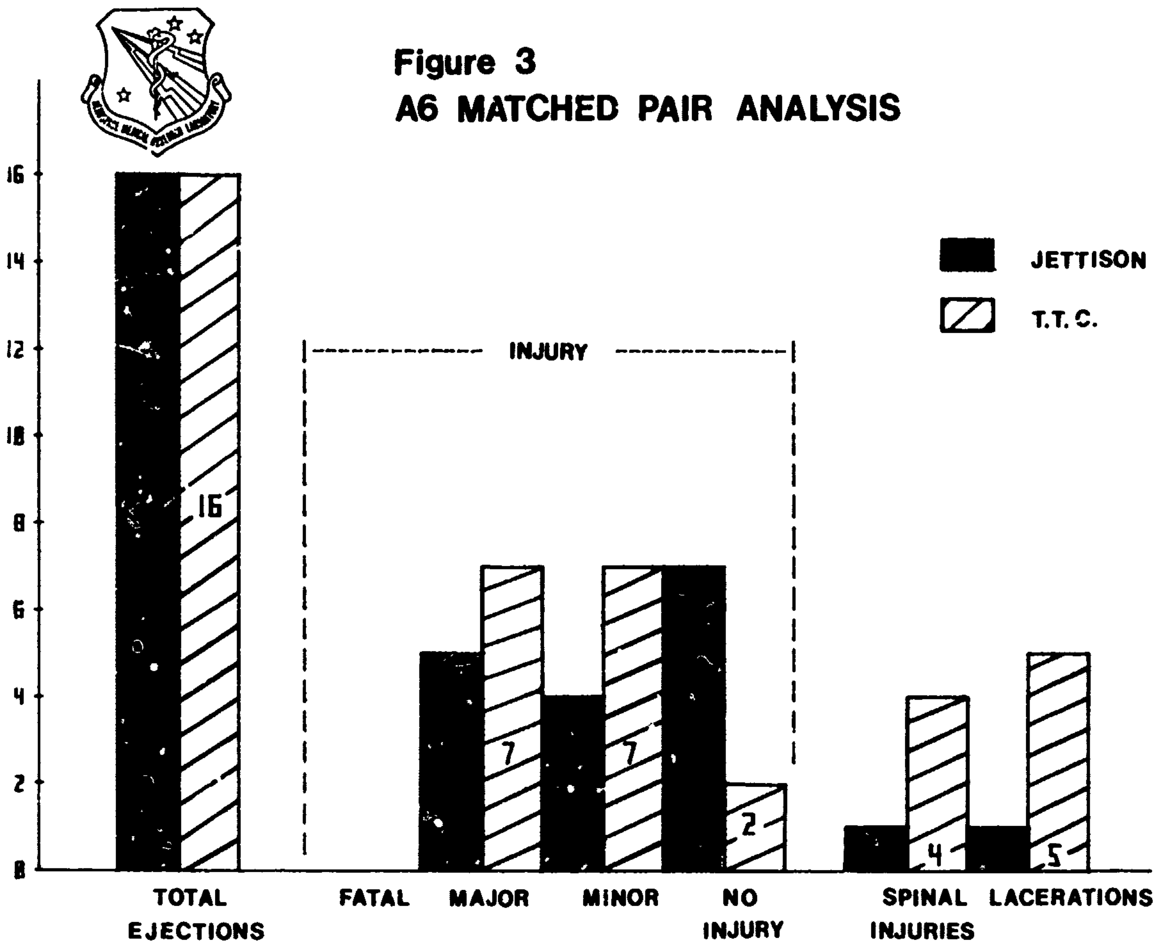


Figure 4
A7 MATCHED PAIR ANALYSIS

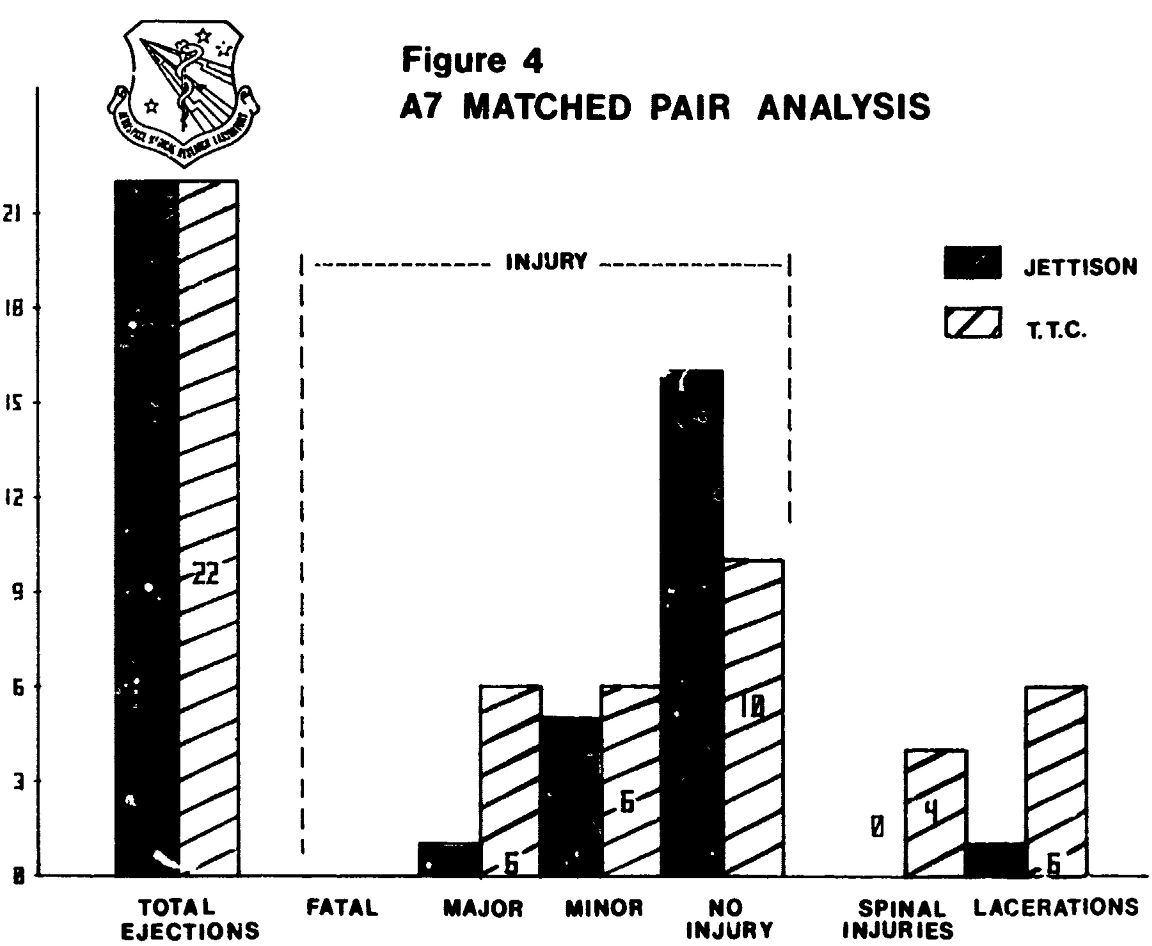


TABLE 1
NON-FATAL A6 MATCHED

	THROUGH-THE-CANOPY		CANOPY JETTISON	
	ALTITUDE	VELOCITY	ALTITUDE	VELOCITY
	[redacted]	[redacted]	[redacted]	[redacted]
	2500	210	2000	200
	2500	210	2900	221
	800	135	900	120
	800	135	1000	120
	[redacted]	210	[redacted]	200
	500	180	600	200
	8000	225	5600	230
	8000	225	3800	215
	[redacted]	[redacted]	[redacted]	[redacted]
	13500	[redacted]	12000	[redacted]
	1800	180	1200	250
	1000	210	2500	250
	6000	320	2500	250
	6000	320	3000	250
MEAN	4256	216	3419	213
STD DEV	4189	52	3585	42

TABLE 2
NON-FATAL A7 MATCHED

	THROUGH-THE-CANOPY		CANOPY JETTISON	
	ALTITUDE	VELOCITY	ALTITUDE	VELOCITY
	[redacted]	30	[redacted]	15
	[redacted]	[redacted]	[redacted]	[redacted]
	7000	300	7800	290
	[redacted]	220	[redacted]	210
	[redacted]	[redacted]	[redacted]	[redacted]
	200	[redacted]	300	[redacted]
	[redacted]	[redacted]	[redacted]	[redacted]
	[redacted]	75	[redacted]	80
	[redacted]	260	[redacted]	275
	[redacted]	100	[redacted]	90
	2000	350	1900	300
	[redacted]	165	[redacted]	180
	[redacted]	10	[redacted]	30
	800	150	900	140
	[redacted]	[redacted]	[redacted]	[redacted]
	2000	350	3000	330
	[redacted]	130	[redacted]	125
	[redacted]	[redacted]	[redacted]	[redacted]
	[redacted]	[redacted]	[redacted]	[redacted]
	[redacted]	180	[redacted]	200
	800	160	900	170
	[redacted]	50	[redacted]	90
MEAN	1800	179	1890	179
STD DEV	2468	99	2558	91

Figure 5

KNOWN SPINAL FRACTURE LOCATIONS (NAVY)

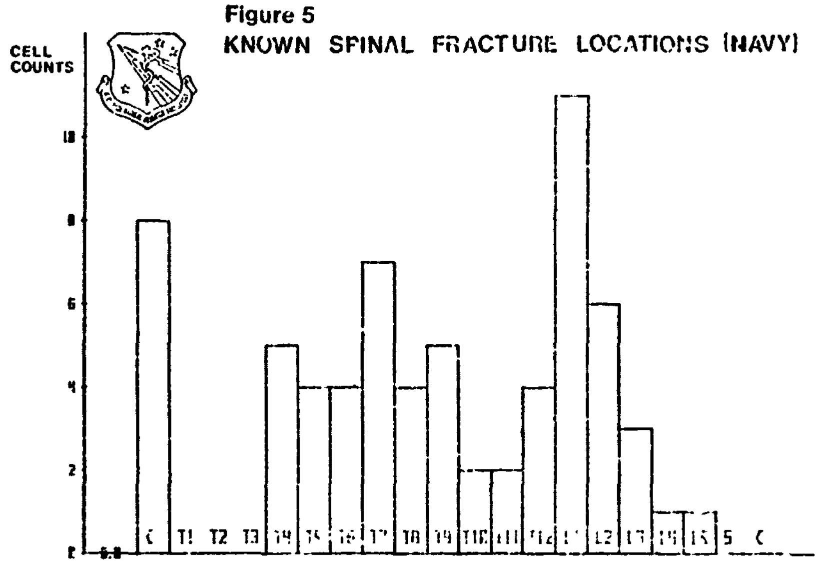


Figure 6

KNOWN SPINAL FRACTURE LOCATIONS (AIR FORCE)
(1964-1970)

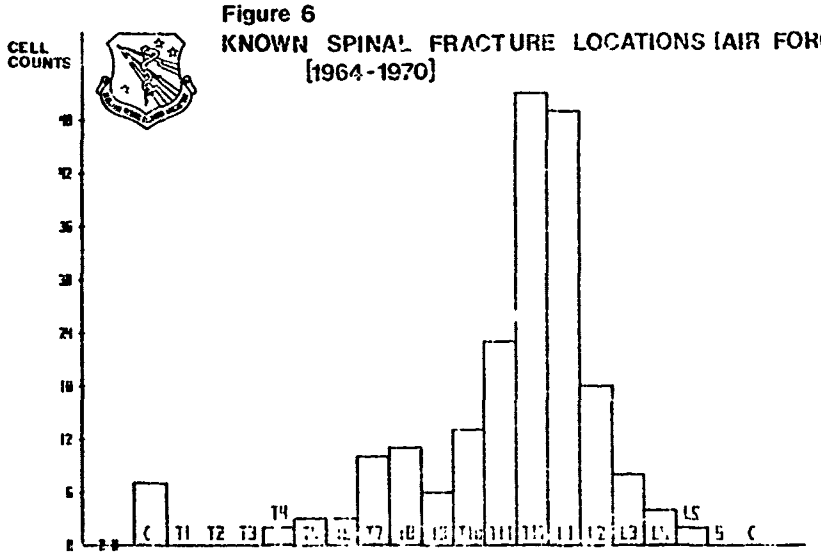
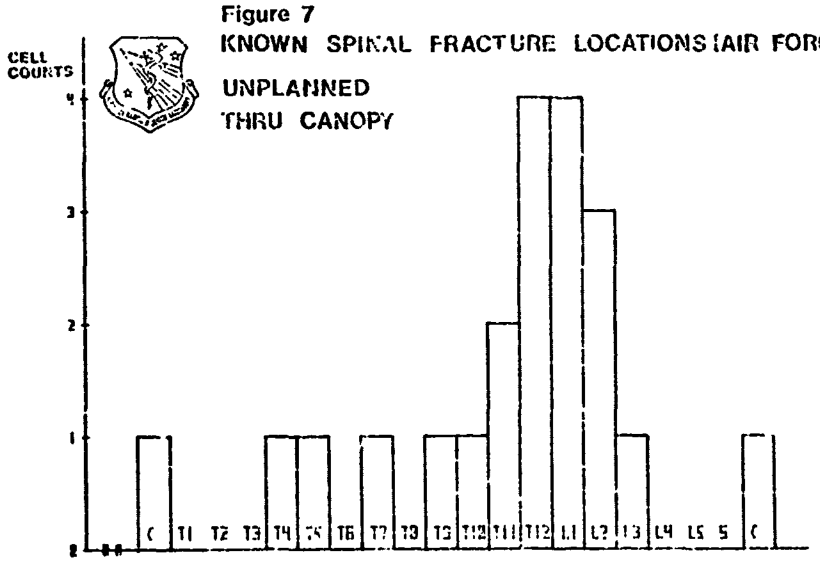


Figure 7

KNOWN SPINAL FRACTURE LOCATIONS (AIR FORCE)

UNPLANNED
THRU CANOPY



An alternative to the TTC approach is more rapid canopy removal. Some newer systems achieve this, but the residual time delay penalty seems to be about 160 milliseconds even at high speed. The most desirable system would produce a greater decrease in the delay. Since we are dealing with a problem where a solution may yield only a small benefit, it seems ill-advised to spend large sums to correct half of it.

TORSO RETRACTION EXPERIMENTAL DATA

Turning to the problem of upper torso retraction, current ballistic inertia reel specifications appear to be based on present canopy removal times rather than on human tolerance to the retraction provided by the reel.(6) In order to assess the potential for shortening this time, a series of human volunteer tests was performed at the Aerospace Medical Research Laboratory (AMRL) at Wright-Patterson Air Force Base, Ohio. These tests included 179 human exposures during the period from January 1978 to April 1979.

The AMRL Body Positioning and Restraint Device (BPRD) was used to accomplish upper torso retraction. The BPRD is a hydraulically actuated retraction system designed to simulate the force-time history of a powered inertia reel.(6) The subject wore a helmet and USAF restraint harness and was seated on an instrumented seat which allowed recording of the inertial forces reacted by the subject into the seat pan and seat back. The subject was restrained by a conventional seat belt and torso harness. Force transducers were used to measure loading applied to the subject. The shoulder straps were attached to the torso harness using standard Koch fittings. The other ends of the shoulder harness were attached to the retraction cable of the BPRD. The cable was extended by a measured amount prior to each test. The subject was asked to lean into the harness and maintain 10 to 20 pounds of force to simulate the normal reel retraction tension. The actual value was displayed to the subject on a digital meter. The signal was derived from a force cell linked to the retraction cable. At initiation, the subject was retracted by the hydraulic actuator and impacted the instrumented seat back. Head and chest accelerations were approximated using triaxial accelerometer arrays applied over the subject's sternum and fixed to the maxillary teeth. Subjects participated no more often than once per week. Medical supervision included pre-test and post-test physical examinations and blood pressure measurements as well as continuous electrocardiographic monitoring with a medical officer in attendance. Twenty-two subjects participated during various stages of the program, 20 males and 2 females. Each subject followed a sequence of gradually increasing retraction lengths and/or hydraulic pressures. A sequence of pictures illustrating a typical retraction is included as Figures 8-11.

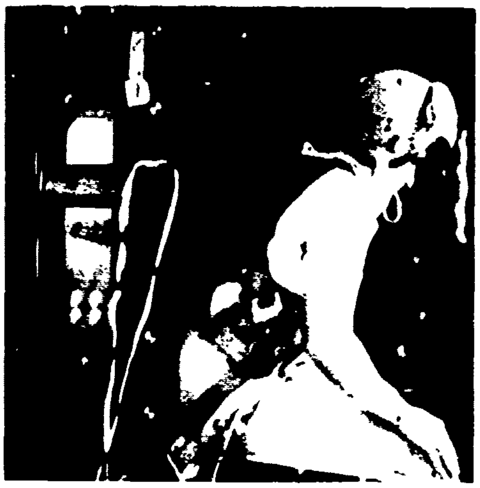


Figure 8
0 Milliseconds

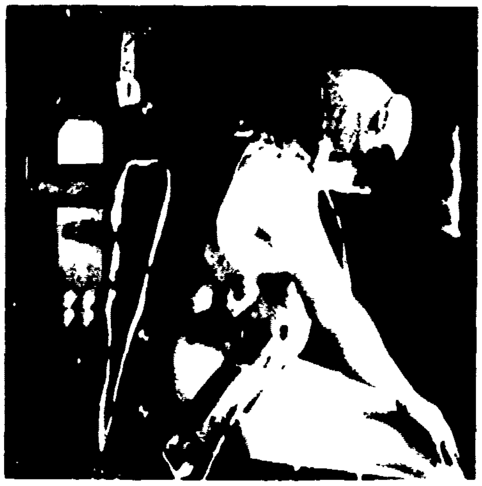


Figure 9
49 Milliseconds

Figure 10
101 Milliseconds

Figure 11
139 Milliseconds

10 INCH (25.4 CM) RETRACTION SEQUENCE

Although operational reels generally provide 18 inches (45.7 cm) of retractable length, it has been found that a portion of that length is used in order to extend the shoulder straps to reach the attachment fittings of the torso harness. The practical maximum retraction distance is approximately 14 to 15 inches for a crewmember grossly out of position. Such a situation is probably most likely in a multiseat aircraft in which a crewmember may be ejected unprepared in an aircraft undergoing high G maneuvers, or in an accidental or automatic ejection. The AMRL experiments investigated retraction distances of 10, 12, and 14 inches (25.4, 30.5, and 35.6 cm).

The results of these tests indicated that retraction of the human torso in a one G field could be safely performed in much less than 300 milliseconds even through large distances approximating the maximum extention of a typical reel. The means and standard deviations for selected parameters are presented in Table 3. (The "PSI" notation denotes the hydraulic pressure used to produce the retraction). Figure 12 presents a plot of peak cable force versus retraction time. It can be seen that a point of diminishing returns is eventually reached in which large increases in cable force produce only small decreases in retraction time. All measured parameters appear to be well within human tolerance. The subjects tolerated the procedure well in all cases and generally reported enjoying the experience.

Several other points are worthy of note. The retraction time was defined as the time from the onset of cable force to the peak of seat back force. Approximately 10 milliseconds should be added to the reported retraction times to allow for the uncertainties in the timing of the pyrotechnic element in the inertia reel. Peak seat back force appeared to be a reasonable retraction completion criterion. Some subjects had continuing head erection movement following this point, but others maintained a head-forward position. The optimum time for ejection initiation, therefore, could not be based on head orientation after retraction. This would be particularly true in retracting a subject whose torso was already on the seat back.

One experimental condition purposely did not reproduce an operational retraction. In our tests, the subject was fastened to the cable with the piston fully retracted and adjusted for comfort. This assured that no significant afterload would be placed on the subject by the hydraulics after retraction. Such is not the case in the cockpit since the inertia reel generally does produce an afterload. A future test series is planned at AMRL with applied afterloads. It is anticipated that the forces and accelerations at seat back contact in this case will be more severe. It should be recognized however, that although the reported experiment does not duplicate the operational system in all respects, the operational configuration could be made to duplicate the experiment, if desired, by a procedural change and the provision of adjusters on the harness.

A final point concerns head impact against the backrest at the end of retraction. During developmental tests for the human test series, anthropomorphic dummies were utilized to determine expected force levels. The dummies experienced head impacts in the range of planned human exposures. Some of the impacts were of such great force that helmet fractures occurred. Our analysis indicated that active neck muscular effects in the human would significantly reduce the head velocity at impact allowing a safe exposure. Furthermore, human tests at low levels indicated that the dummy tests predicted higher accelerations than were observed with volunteers. We therefore proceeded with the planned exposures and, to our surprise, observed no significant head impacts at all. This points up once again the critical need for continued live human subject testing. Particularly when designing systems intended to be safe, knowledgeable developmental testing with living subjects can yield invaluable data for optimized designs, allowing demonstrated safe performance at levels which would appear to be injury levels using dummies, human cadavers, or animals.

Table 3. RETRACTION TEST PARAMETERS

	Retraction Length 10 Inches		Retraction Length 12 Inches		Retraction Length 14 Inches	
	600 PSI	900 PSI	600 PSI	900 PSI	600 PSI	900 PSI
1. Retraction Time (Seconds)	148 (8.2)	134 (11.5)	167 (9)	144 (9)	190 (12)	158 (10)
2. Peak Cable Force (Pounds)	185 (24.3)	250 (28.5)	188 (19.4)	259 (35.6)	198 (24.3)	286 (34.9)
3. Average Reel Retraction Velocity (Feet/Second)	77.9 (2.4)	97.4 (2.7)	87.2 (2.3)	108.5 (4.1)	86.1 (2.5)	110.9 (3.5)
4. Peak Seat Pan Force (Pounds)	75 (18)	102 (23.4)	96 (21)	118 (34)	109 (31)	146 (40)
5. Peak Lower Back Force (Pounds)	*	*	91.2 (41.1)	86.2 (41.4)	106.3 (31.8)	109 (29.8)
6. Peak Upper Back Force (Pounds)	354 (71)	466 (70.6)	365 (77.8)	512.4 (111.2)	326.3 (48.7)	463 (106.6)
7. Peak Chest Acceleration						
a. Retraction (G's)	7.2 (1.4)	11.6 (1.5)	8.2 (1.9)	11.8 (2.6)	6.9 (1.4)	11.5 (2.1)
b. Seat Back Impact (G's)	7.5 (1.2)	11.9 (1.9)	10.6 (2.9)	15.4 (3.4)	9.2 (3.4)	13.3 (2.6)
8. Peak Head Acceleration						
a. Retraction Acceleration (G's)	7.1 (1.6)	11.7 (3.0)	9.4 (2.6)	15.7 (4.5)	8.2 (2.1)	15.9 (5.4)
b. Deceleration (G's)	5.9 (2.3)	10.2 (3.3)	7.7 (1.2)	13.5 (3.5)	5.8 (1.3)	12.0 (2.2)

* No Data

Tabulated values are experimental means with the standard deviation in parentheses.

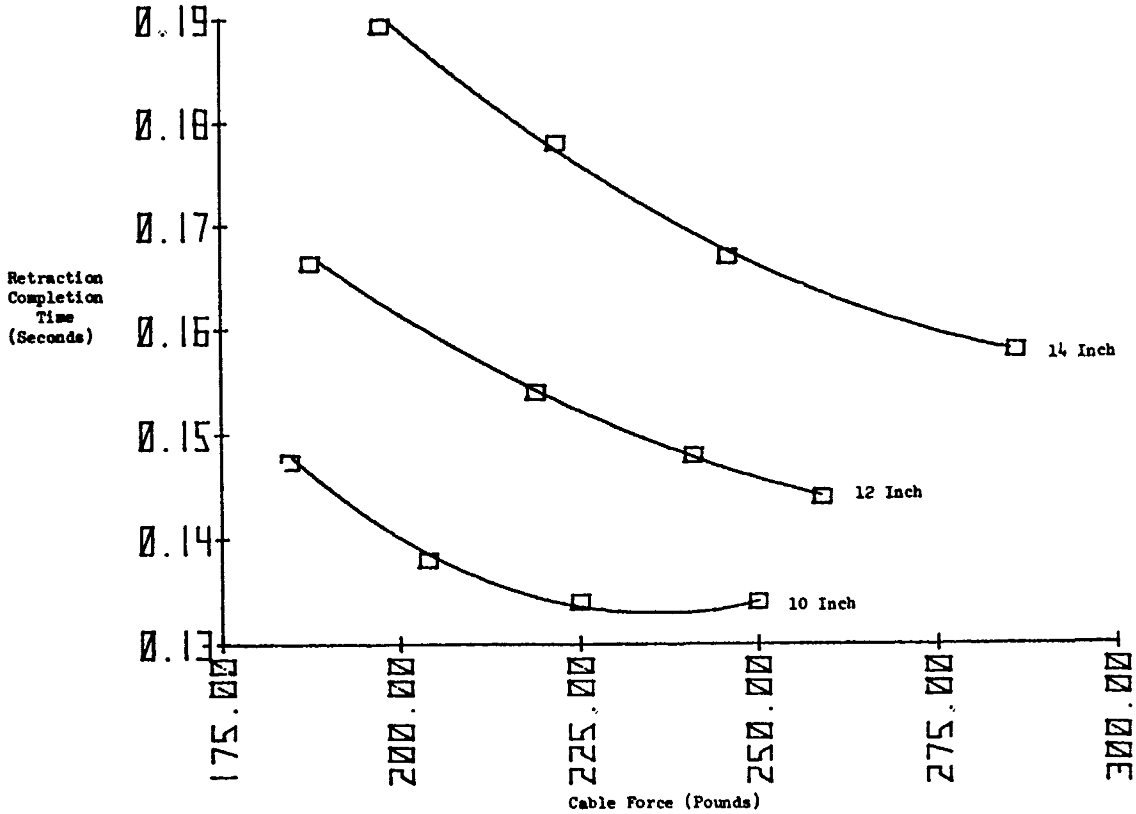


Figure 12. MEAN RETRACTION TIME VERSUS MEAN RETRACTION FORCE

SUMMARY AND CONCLUSIONS

The available evidence, therefore, indicates that small but possibly significant improvements in crew survivability may be realized through a reduction in the sequenced time delay during ejection. This improvement may be undermined to an unknown degree by other ejection injuries or fatalities if the delay is eliminated altogether.

Two general approaches appear to hold promise for attaining an improved overall escape performance. The first approach would involve an improved canopy removal system with a faster system for upper torso retraction as demonstrated in the experimental series. This approach would be limited to a potential improvement of approximately a factor of two over present systems due to the limited capability for canopy removal.

The second, and ultimately the more promising approach would involve an advanced TTC system in which the canopy dispersal pyrotechnics would allow an essentially clear path for crewmember and seat. Furthermore, the TTC initiation would occur at the completion of retraction as measured by an active sensor. Such a sensor could be incorporated in the seat back or in the inertia reel. Should the crewmember be in a nearly desirable position, the ejection would occur almost immediately. Should the crewmember require retraction through a greater distance, the ejection would be delayed by a variable time up to a maximum of approximately 140 milliseconds. A timed ejection would be initiated at that point to insure that an impediment to reel function or sensing would not disable ejection. The human test data presented here indicates potential for safe torso retraction within these times.

Either of the above approaches is amenable to the incorporation of automatic trajectory control and actuation techniques discussed earlier. The second approach would produce a worst case delay of less than half that found in current systems with the average delay (dependent on initial torso position) being much less.

It is recommended that such systems be considered for future manned aircraft having HSLL mission requirements. It is further recommended that additional concerted effort be directed toward the development of new approaches in automatic aircraft emergency sensing and escape sequence actuation. These efforts are necessary to assure maximum likelihood of successful escape from high speed low level flight profiles.

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DISCUSSION

DR. R. AUFFRET (FR)

Un augmentation de la fréquence des fractures du rachis à l'ejection sur le F111 seuible en relation avec le systeme de retraction du torse. Que peusez-vous de cette possibilité?

AUTHOR'S REPLY

No fractures were experienced in the current programme which involved 179 retractions. All forces and loads were well within human tolerance. If some of the fractures experienced in the F/FB-111 were related to retraction (and that has by no means been demonstrated), some evidence suggests that a possible injury mechanism involved the anchoring of the shoulder harness below the shoulder level posteriorly. A current programme is investigating the correction of this design anomaly. We believe these rapid retractions to be quite safe if conventional geometries are maintained.

DR. D.R. MORGAN (UK)

Have you any method of limiting the upward movement of the arms during retraction, especially for passively-ejected personnel?

DR. RADDIN (USA)

For passively ejected personnel, the solution must be in the form of an upper extremity windblast restraint device. This is being explored.

LOW LEVEL, ADVERSE ATTITUDE ESCAPE USING A VERTICAL SEEKING EJECTION SEAT

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ABSTRACT

Recent advances in the development of a Maximum Performance Ejection Seat (MPES), with a vertical seeking capability, address the need for safe escape from aircraft at low altitude, high speed and extreme adverse attitude conditions. The performance specifications of this system, as presently envisioned, will provide safe egress from an inverted aircraft at airspeeds of 0 through 600 knots and altitudes as low as 50 feet above ground level (AGL). The data base and techniques to be used to predict the occupant response consisted of instrumented ejection tests (90 degree and 175 degree roll at 100 feet AGL), mathematical simulations, and graphical analysis of test results. Consideration was also given to the occupant's anthropomorphic properties and physical restrictions such as initial position (as determined by positioning and restraint hardware) and seat configuration.

This paper demonstrates the applicability and efficacy of utilizing biodynamic response simulation and other techniques, not only as a design tool in the evaluation of the physical compatibility of man and ejection system, but also in the evaluation of the ejection system performance.

INTRODUCTION

A threat to aircrew safety is present during all aviation flight operations. This threat is comprised of many interrelated factors. Foremost is the natural and induced hostile flight environment encountered by the aircrew. During combat operations this environment is frequently more severe due to the tactical need to operate the aircraft at extreme limits of the flight envelope. When aircraft are disabled, in combat or due to human or mechanical failure, this threat expands to include the hazards associated with the escape environment.

With the advent of high performance and V/STOL (Vertical/Short Take Off and Landing) type aircraft the probability of an attempted escape from a disabled aircraft in other than level flight, at near ground level altitudes, is increased. Attempted escape from this adverse environment requires improvements to aircrew escape capability and performance.

Despite the success achieved with modern aircrew escape systems, their effectiveness in low altitude, adverse attitudes and high airspeed flight conditions is limited. These escape conditions have resulted in a significant percentage of aircrew fatalities in naval aircraft. To a large extent these ejections were out of safe escape performance envelopes of the particular escape systems involved.

Improvements in adverse attitude escape capability have been recently demonstrated as part of a U.S. Navy development effort (Figure 1). Designated the Maximum Performance Ejection Seat (MPES) this development effort, when complete, will provide major advances in low level, adverse attitude escape capability and improvements in aircrew safety and survivability (1). Since development of the seat is a radical departure from the ejection seats presently employed in Navy aircraft, the evaluation of the various subsystems must consider not only the reliability and maintainability of the associated hardware, but also the man-machine-equipment interface. Techniques that are used to evaluate this interface, however, have not kept pace with the evolution of aircraft, crew station and aircrew equipment design or their operational capabilities. Traditionally these techniques include drawing reviews, mockups, flight tests, as well as track and ejection tower tests. Although important, the usefulness of data acquired by these methods is limited, since it does not take into account the full variability in crew anthropometry and environmental factors, nor do these methods produce adequate triaxial time histories for the purpose of estimating occupant response to particular acceleration profiles.

To evaluate the physical compatibility of crew members with the MPES, the computerized Human Body and Crew Station Modeling System for Motion Studies was utilized (2). This computer model has distinctive advantage in display realism, movement definition, collision and interaction detection and cost effectiveness in real time animation play-back environment. Utilizing this computer model during the development stages of the MPES can serve as both a design tool as well as an effective means of evaluation. Due to the tremendous increase in performance expectation of the MPES it is prudent to obtain proper input data to generate greater computer results.

MPES DESCRIPTION AND PERFORMANCE

The MPES which represents a combination of technological developments, is a significant advancement in the state-of-the-art of escape system technology. These advances are reflected in the following major subsystems (Figure 2).

The Structural Subsystem is a light weight, high strength seating platform which integrates the various other MPES subsystems. It is fabricated of aluminum honeycomb sandwiched between two aluminum sheet facings. Both the core and facings vary in thickness to provide the most efficient structure. Weight of the basic structure is approximately 25 pounds with a demonstrated structural strength capability meeting the U.S. Navy crash safety standards. The structure consists primarily of a seat back with rails, a bucket for housing the seat propulsion and control subsystem and a seat lid mounted on top of the bucket. Unlike other seats which house the recovery subsystem within a head box or in back of the crewmember, the area between the guide rails of the MPES has been reserved for the recovery subsystem in addition to other key components. Contoured space on the front surface of the seat back has been allocated for a "soft pack" survival kit which is a departure from the present day cumbersome Rigid Seat Survival Kit (RSSK). The aluminum honeycomb structure permits the internal routing of control cables and electrical lines for maximum shielding and protection.

The Survival Subsystem is mounted on the seat back in the lumbar region of the occupant. This pack contains, in addition to all of the conventional emergency survival equipment, an oxygen accumulator for emergency breathing. Emergency oxygen is supplied to the accumulator by an inert chemical oxygen generating system, thereby eliminating the need for interfacing with liquid oxygen stores aboard air-capable ships and risking the hazards associated with frequent checking and maintenance.

Occupant Positioning and Restraint is provided by a series of active and passive components working together to keep the crewmember securely restrained in the seat during emergency escape but unimpeded during his normal mission performance routines. It consists of a contoured and adjustable headrest, extending seat side panels, ballistic inertia reel, inertia reel strap cutter, automatic lap belt retraction and release devices, and a leg restraint and positioning system.

The headrest acts to support the head during normal take-off and flight conditions. For catapult take-off, the headrest is manually adjusted to its full forward position to support the crewman's head. In this position, the crewman can keep his eyes focused on the instrument panel displays during the catapult stroke. Upon initiation of ejection, the headrest automatically retracts into the full aft position to insure proper head alignment for the ensuing upward acceleration.

The inertia reel is a device from which two straps are connected to a standard torso harness. At the time of ejection the inertia reel is gas actuated and retracts the crewman's shoulders back to the seat as part of the spiral alignment procedure. The seat back contour provides support and occupies the area extending from seat bucket to the height of the inertia reel take up straps. The seat back/inertia reel geometry precludes the possibility of arcing hyperextension of the upper thorasic spine as a result of the scapulae pivoting around the upper portions of the seat back in response to inertia reel activation (3).

The lap belt retraction mechanism is activated by the same gas source as the inertia reel. The retraction operation tightens the lap belt to anchor the crewman's hips and to prevent "submarining" upon ejection. Both the inertia reel and lap belt straps are released automatically as part of the seat/man separation sequence. As an option, the powered inertia reel can function in a recyclable mode to provide the crewman with a powered and controlled retraction within the cockpit. This system permits the pilot to regain proper seating position in the event he is thrust out of his seat by adverse flight conditions or out of controlled flight.

The Recovery Subsystem takes advantage of the large amount of free space available between the seat guide rails. Its placement on the smooth back surface of the seat gives the best assurance that it will not entangle with seat structure. It consists of a seat back mounted chute extraction motor and a vacuum sealed parachute packaging system. The system provides the pilot with the optimum in reliability through the use of a microprocessor control system to precisely time the sequence of events in deploying the pilot/drogue chute and the main recovery chute. The development of the Sealed to Reduce Maintenance (STORM) parachute packing concept permits the parachute to have a 5 to 7 years service-free life and thus eliminate the requirements for a paraloft aboard air capable ships, frequent (217 day) repack cycles and costly logistics and manning support (4).

The Propulsion and Control Subsystem, located under the seat and utilizing a major portion of the seat bucket (Figure 2), provides the MPES with a unique seat steering and stabilization capability. The recent results of this development effort demonstrated the feasibility of improving the safe ejection envelope to permit successful ejections from inverted aircraft at a height of 50 feet above ground level and ground level escape at aircraft attitude of up to 90 degrees of roll. Two of the major elements of this subsystem are the propulsion steering unit and the autopilot. Two, long thrust time, spherical rocket motors, independently moveable and driven by hydraulic actuators make up the propulsion steering unit. The autopilot, which generates the steering commands to the propulsion steering unit, consists of three rate gyros and a microcomputer. The microcomputer also controls the timing and sequencing of events in the system.

PERFORMANCE DEMONSTRATION TESTS

In an effort to demonstrate the concept feasibility of the vertical seeking aspects of the MPES a series of flight tests were conducted (5). The two most significant of these ejection tests were initiated from a cockpit section suspended 100 feet above ground level. In these two tests the cockpit was oriented to a 90° and 175° roll attitude, respectively. The seat trajectory plots of these tests (elevation vs time) are illustrated in Figure 3.

Prior to these tests the seat and dummy were instrumented to provide input data useful in the determination of force parameters affecting the seat occupant. The instrumentation and data presented herein concentrates on the 175° roll attitude test. The configuration of the propulsion and control subsystem tested contained one spherical rocket motor mounted in a two axes gimbal ring. This arrangement, which provided seat control in only two axes, made it possible to demonstrate the feasibility of the vertical

seeking concept and in addition obtain significant data. The development of the configuration having two rocket motors, Figure 2, was pursued subsequent to the feasibility demonstration tests discussed herein.

The two motor arrangement will provide seat control in the three axes (pitch, roll and yaw) to diminish the effects of cross coupling, provide increased position control in an aerodynamic environment and aid in proper seat orientation for parachute deployment.

Two triaxial linear accelerometer packages were surveyed on the seat and these, together with three dimensional angular rate sensor data, provide a complete three dimensional time history of any portion of the seat. Figure 4 shows the monitored X Y Z linear accelerations. The acceleration measured on the occupant seat system used the following coordinate notation: +X, eyeballs out; +Y, eyeballs right; +Z, eyeballs down.

The dummy (Figure 5), was instrumented with a triaxial linear accelerometer package and three dimensional rate gyros mounted in the chest cavity. Additionally, triaxial linear accelerometers were mounted on the right leg to detect possible strikes between the dummy and crew station which might effect seat trajectory. Similarly, the dummy head was instrumented using a three dimensional linear accelerometer package. Since these two tests were primarily feasibility demonstrations the head and lower leg joints were tightened significantly to prevent adverse motion of the dummy relative to the seat. Linear accelerations monitored at the dummy's chest are shown in Figure 6. Yaw, pitch and roll rates monitored at the dummy's chest are shown in Figure 7. The data obtained from the 175° roll attitude test identified a maximum dummy acceleration of +13 G_z monitored at the foot. Maximum head, chest and seat bucket accelerations were +11 G_z. These monitored linear accelerations (by themselves) are less than those presently experienced in ejection seats in the Navy inventory. The effect of combined linear and angular acceleration components however has not, as yet, been quantified.

SIMULATION

In order to be able to estimate occupant response to a given acceleration profile, the seat time history has to be well defined over the time of interest. It therefore becomes crucial that both the seat and dummy be properly instrumented so that modification to the seat-man driving function can be related to changes in occupant response. As was pointed out previously, seat and dummy instrumentation locations must be surveyed to readily identifiable landmarks so that the effects of the seating and restraint can be estimated.

Occupant dynamic response simulation (as related to ejections) poses some problems in extrapolating beyond test data. This is due to the fact that one is dealing with a closed loop system, where occupant motion within his seating and restraint system can significantly alter the trajectory achieved which in turn is the driving function of the seat-man system. This differs from other cases (such as crash simulation) where the mass of the vehicle is such that the response of the occupant to the crash pulse leaves the driving function (time history of the seat) unaltered. During the initial phases of an ejection however, when man-machine interface is of major concern, the trajectory and seat forces are well defined since the seat is still on the rails and propelled by the catapult.

Mathematical modeling has been used to replicate the test conditions previously described. Since the dummy's joints are significantly tightened, as was the restraint system, the accelerations monitored on the seat were not significantly different from those on the dummy, when translated to a common coordinate system. The effectiveness of modeling will be realized when the existing test conditions are relaxed. The effect on occupant response, with loosening of the joint characteristics (allowing segment motion) as well as introduction of restraint harness slack, can then be effectively analyzed. Additionally, magnitude of segment motion can be interpreted in terms of possible effects on trajectory (i.e. flailing, C.G. shifts, etc.).

Occupant response to acceleration profiles can be directly related to initial position of the crew member relative to the crew station as well as the initial inertial conditions of the aircraft. Since the preliminary dimensions of the MPES have been defined, problems in seat-aircraft interface can be isolated using the Bioman simulation package (2). Presently, the seat is being evaluated in terms of the AV-8B crew station geometry. Assuming that the crew member is seated at the design eye reference point, the seat and crew station geometry was used to define an idealized seating position (2). Using these initial segment positions, the monitored seat acceleration time history was used to drive the seat-man system. Occupant motion, relative to the crew station, was analyzed in terms of crew member-crew station compliance. The initial phases of the ejection are shown in Figure 8. The seat trajectory, in relation to the aircraft, is shown in Figure 9. Although still in the preliminary stages, the use of mathematical modeling will complement and expand the test data available and help to quantify specific configurations that will maximize the efficiency of the future track tests to be conducted.

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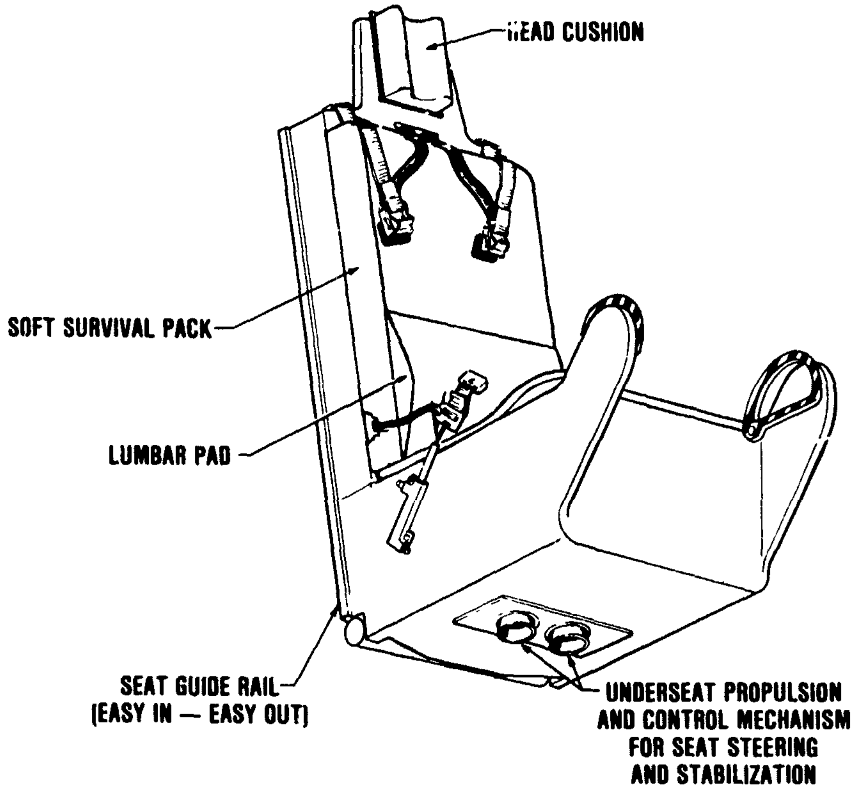
Fig.1 Composite of feasibility demonstration test, 175 degree roll attitude



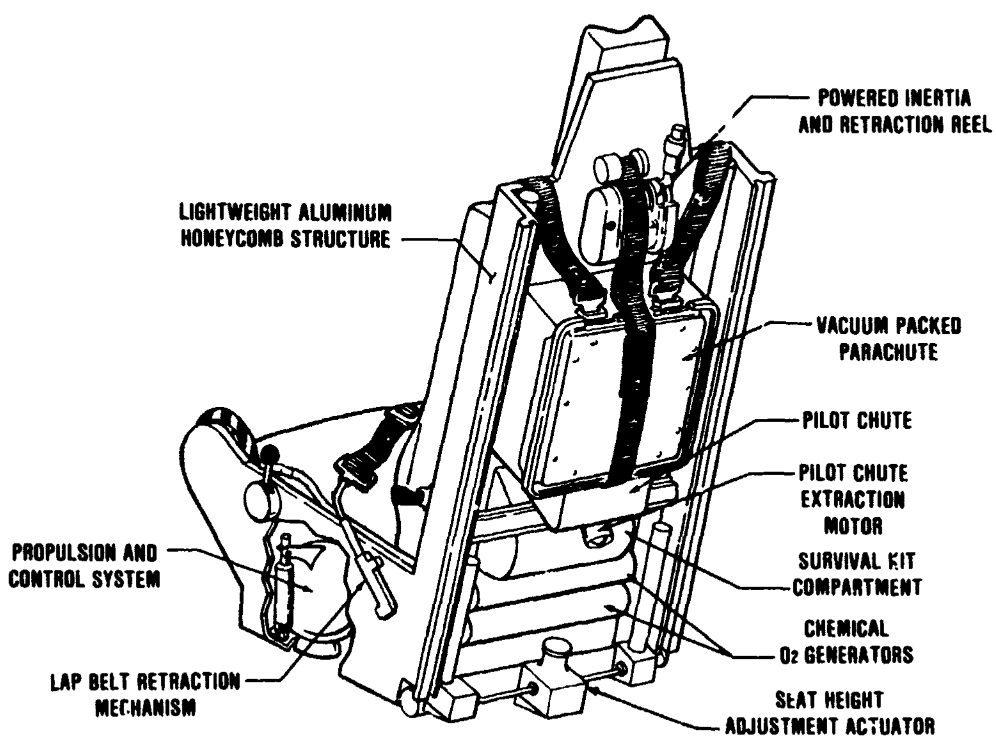


Fig.2 Maximum performance ejection seat (MPES)
Top – front view
Bottom – rear view

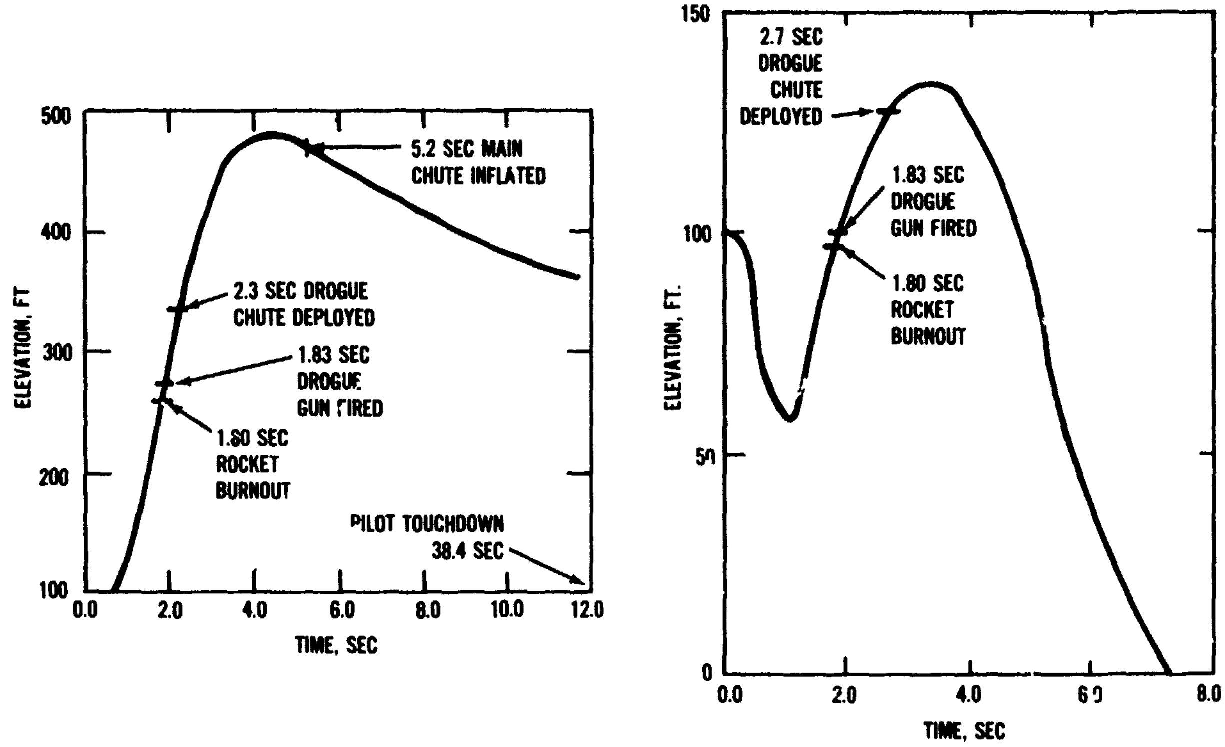


Fig.3 Trajectory plots
Left – 90 degree roll attitude ejection
Right – 175 degree roll attitude ejection

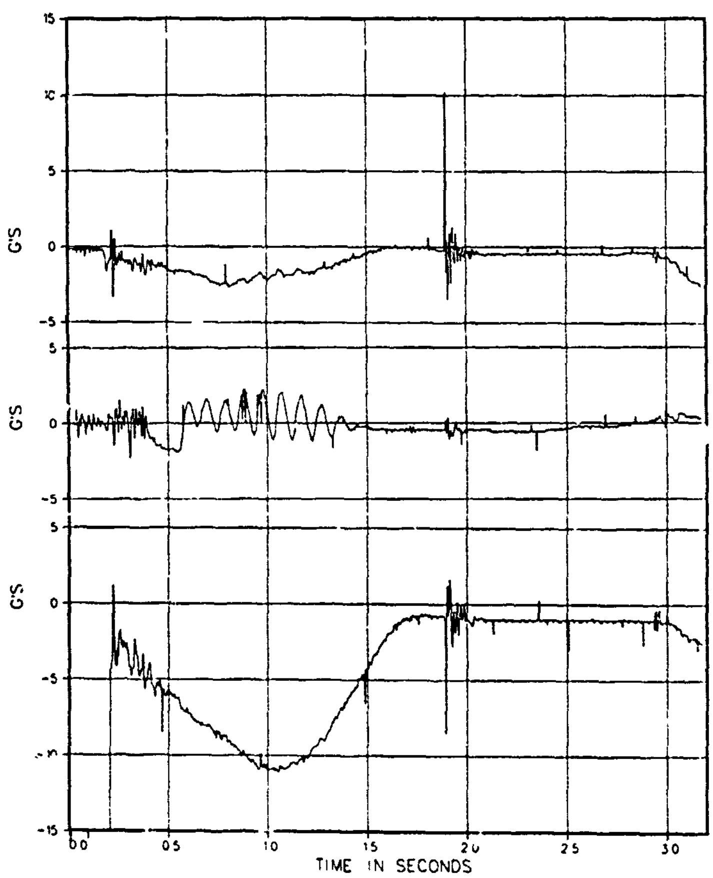


Fig.4 Monitored seat accelerations time histories
Top – X
Middle – Y
Bottom – Z

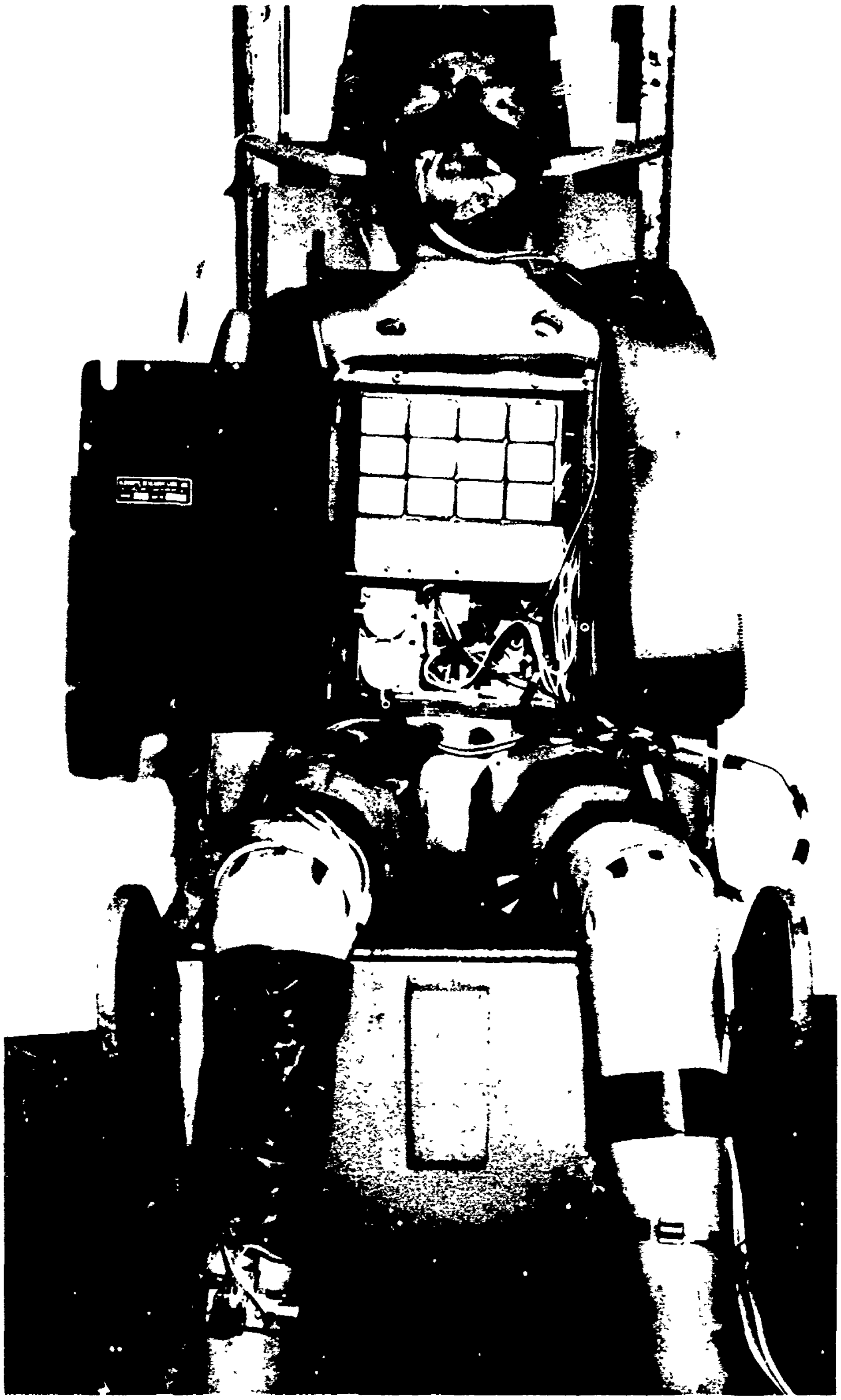


Fig 5 Dummy instrumentation packages

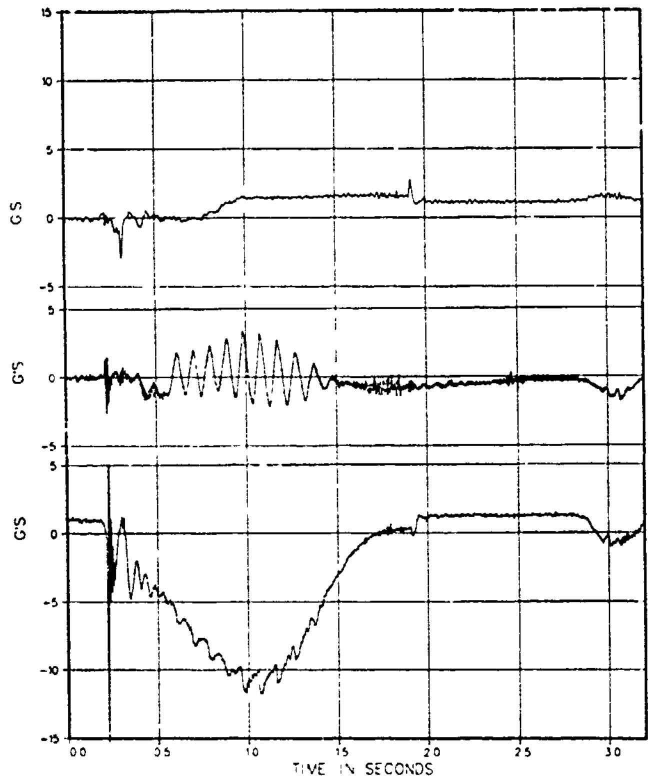


Fig.6 Monitored dummy chest accelerations time histories
Top – X
Middle – Y
Bottom – Z

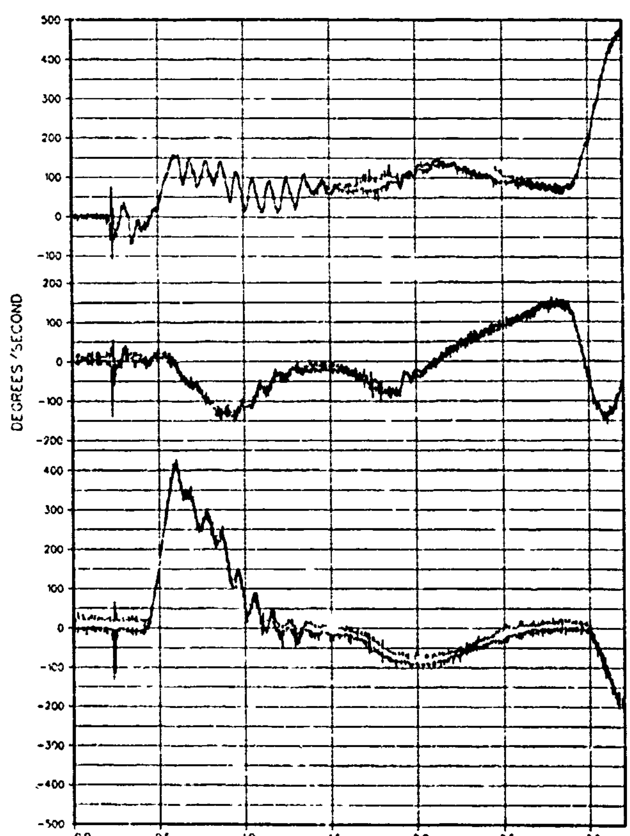


Fig.7 Monitored dummy chest angular velocities
Top – yaw
Middle – pitch
Bottom – roll

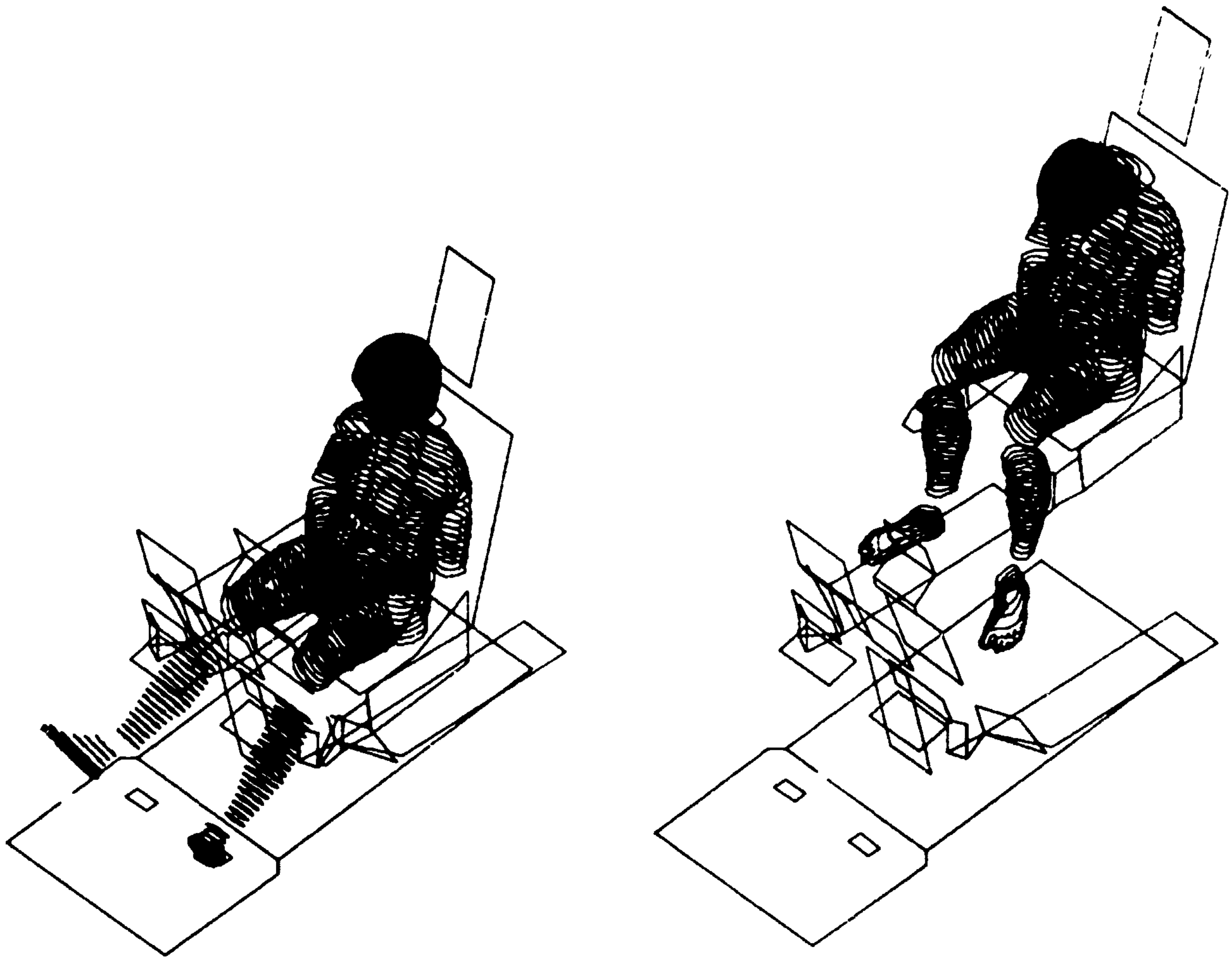


Figure 8

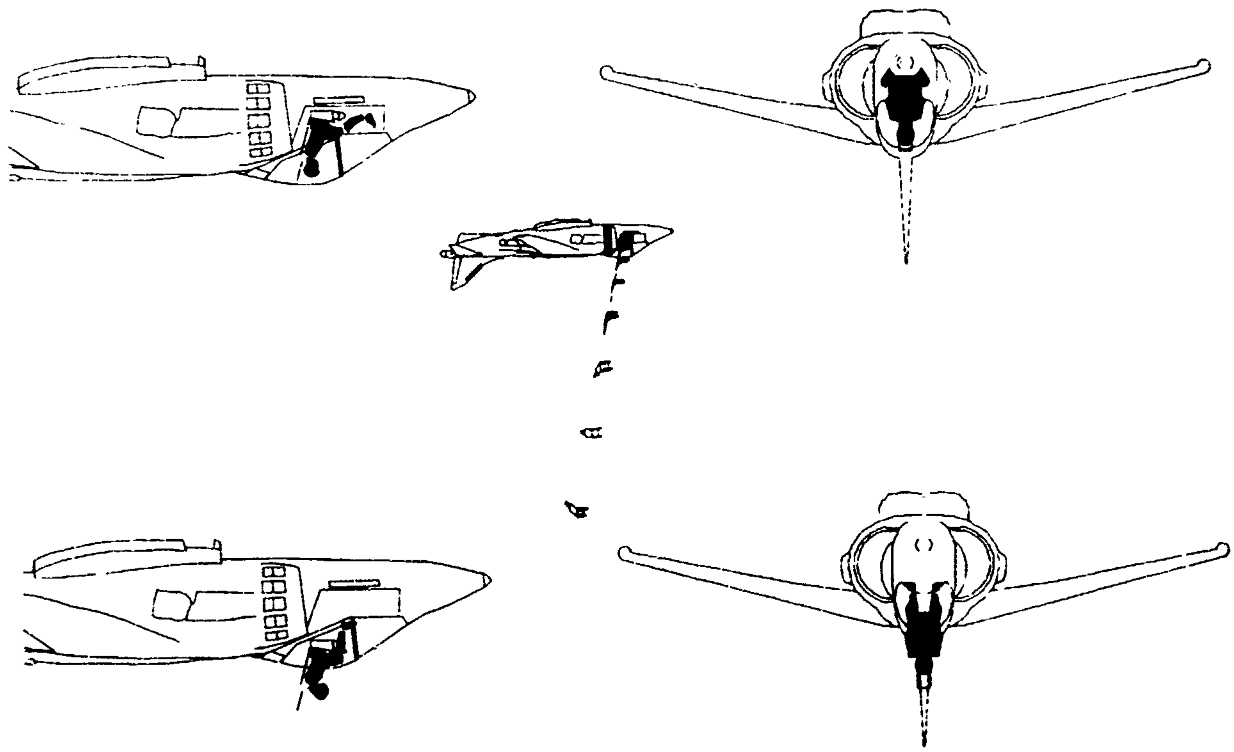


Figure 9

CONCLUDING REMARKS BY SESSION CHAIRMEN

E.C.BURCHARD
H.T.ANDERSEN
A.J.BENSON
J.COLIN
S.A.NUNNELEY

CONCLUDING REMARKS BY SESSION CHAIRMEN*

Part I. Ride Quality and the Effect of the Physical Environment (Dr Eduard C. Burchard, FRG)

Four papers were presented in this part and it became clear that the physical environment in the use of the third generation military high performance aircraft plays a more vital role than ever due to the high speeds involved, and especially due to the tendency toward ever lower flying, i.e. flying closer to the ground. This calls for the best possible analyses of meteorological conditions and their forecast to aircrew; in the real war situation there also will be intensive battle-field activity that might drastically change terrain and especially meteorological condition in such a way that additional measures are necessary to enable the flight-crew to cope with the visibility-deterioration in the respective situation.

Active control systems are under development to reduce pilot's workload and the physical stresses encountered during flight in adverse meteorological conditions; a variety of technical ways in the field of alleviation of ride-bumpiness by the use of ride smoothing systems for instance can be seen; further research in this direction is necessary.

After many years of operational experience in HSLL-flying, the majority of test pilots and operational crews are in agreement with the statement that in the HSLL environment not only the pilot's effectiveness is adversely affected, but also that problems of physiological tolerance are becoming apparent.

Several outstanding movie-films addressing various aspects of the operational characteristics of presently used HSLL aircraft illustrated the above mentioned problems.

In view of growing surface-to-air anti-aircraft weapon development it can be foreseen that with the new generation tactical aircraft in an anticipated surface-to-air oriented high threat combat environment, there has to be a definite emphasis on continuous development efforts for automated systems integrating components within the cockpit affecting aircraft controls and weapons delivery systems. The goal of accomplishment of successful mission dictates continuous effort for biotechnological improvement in order to ease the load from the aircrew who in the past in many cases have been brought to the limit of physical and psychological tolerance.

Part II. Thermal Effects of High-Speed, Low-Level Flight (Dr Harold T. Andersen, NO)

In summarising this session, we may say that high-speed, low-level flight may cause excessive thermal loading of aviators due primarily to solar radiation by the so-called greenhouse effect, but also due to the aerodynamic heating, the heat generated on board by avionics, and the increased metabolic heat produced by the demanding physical workload in flight. The aviator is frequently at a disadvantage as far as unloading excessive heat is concerned due to his multi-layer flying clothing and the hot and sometimes humid cockpit environment which very adversely interferes with the dissipation of heat. It has been clearly demonstrated, I think, that pilot overheating may lead to a decrement in task performance, decreased G tolerance and fatigue. Thermal stress, thus, has been identified as an environmental factor which may cause hazardous flying conditions. Most fighter aircraft in current use have been designed with but little emphasis placed on the thermal comfort of crew members, as anyone who has flown them will readily testify. The new generation of fighter aircraft, among them the Tornado, the Mirage 2000, and the F16, reportedly have very much better cabin conditioning systems than their predecessors, although the resulting noise levels may be excessive; a factor which constantly needs to be considered. If one accepts thermal overload as a serious risk factor in high-speed, low-level flight, we would like to submit the following recommendations. The specifications for the cooling capacity of an aircraft and environmental control system ought to be man orientated as was appropriately emphasised in this session. If a cockpit conditioning system is chosen it should be effective, and at the same time it should not introduce new undesirable factors such as a high noise level, or carry a great weight penalty, or adversely affect the thrust to weight ratio of the aircraft in order to function properly.

Part III. Vibration Effects of High-Speed, Low-Level Flight (Dr Alan J. Benson, UK)

The eight papers presented in this session fell into two broad categories, those that dealt with the transmission of vibration through the body, and those that described impairment of performance produced by whole body vibration. These two areas of research are complementary in so far as an accurate description of the transmission of vibration from the aircraft structure to different parts of the aviator's body should permit a reliable prediction to be made of the effect of a given vibration environment on a particular aspect of performance, such as vision or manual control. However, the complexity of an adequate biodynamic model was made very apparent by the papers which described the transmission of sinusoidal vibration (predominantly z axis vibration) to different parts of the body. For example, motion of the head, measured in different studies by displacement and acceleration (linear and angular) transducers, in response to a sinusoidal z axis vibration is not simply a translational movement in the z axis, but involves translational and angular movement in all three orthogonal axes. In addition, at certain frequencies (principally 2-4 Hz) the dominant angular movement of the head is at the second harmonic of the forcing frequency.

The difficulty of developing an adequate biodynamic model was substantiated in different ways by the various contributions. Measurement of mechanical impedence showed how readily transmission was modified by muscle tone, even in a restrained seated posture. Changes in the seat back angle were also shown to alter transmission to the head - a factor of some concern in view of the possible introduction of reclined seats (with high back angles) to increase G tolerance in future air-combat aircraft. A further and unwelcome complication of the biodynamic model was the demonstration in the

amplitude spectra of head acceleration of non-linearity in transmission characteristics as a function of vibration intensity.

The impairment of vision by vibration has long been recognised, and design principles for achieving maximum legibility of instrument displays are well established. However, the problem of modelling visual performance in a vibration environment is a formidable one. Even when the angular and linear motion of the head is known and a reliable assessment of the relative movement of the eyes with respect to the visual target can be made, target variables, such as size, contrast, luminance, colour, conspicuity and background structure, all influence the probability of a target being correctly perceived. While an adequate model has yet to be developed, work in this area has provided useful information on neural mechanisms controlling eye movements and upon the degradation of visual acuity associated with movement of the retinal image.

Other papers dealing with the effects of vibration on performance were more pragmatic. One demonstrated that a new, high luminance, numeric display could be read with few errors during vibration; another examined the effect of vibration on the accuracy of aiming a helmet-mounted sight. The latter study showed that during simulated turbulence, accuracy was appreciably degraded by low frequency (< 4 Hz) angular head movements which limited the usefulness of the system to coarse weapon aiming. Techniques involving the filtering or scaling of the head position signal showed promise for improving accuracy in specific applications.

Although the papers presented in this session were of value, in so far as they extended knowledge of the effect of vibration on man, all the studies were concerned with the effect of either simple sinusoidal vibration or the vibration spectra of old aircraft. Regrettably there was a lack of information on the vibration environment of the next generation of aircraft, designed for flight at high speed and low level, in which high wing loading and active ride smoothing systems should materially ameliorate, if not prevent, the deleterious effect of vibration on aircrew performance.

Part IV. Cockpit Design and Aircrew Workload (Dr J. Colin, FR)

Les communications présentées au cours de la session intitulée "conception du poste de pilotage et charge de travail de l'équipage" peuvent se classer en deux groupes inégaux. Le premier groupe ne concerne qu'une communication, celle de Monsieur H. MUTSCHLER qui a présenté une étude ayant trait à la détection d'objectifs sur un écran de télévision montrant le sol défilant sous la caméra d'un engin téléguidé de reconnaissance. Bien que correspondant à une étude sur le personnel au sol, les conclusions tirées sur les paramètres influençant le taux de détection sont cependant applicables aux problèmes de présentation des informations dans un poste de pilotage. Le deuxième groupe a plus précisément concerné le sujet de la session et peut se subdiviser lui-même en deux parties portant :

1°/ sur les dispositifs de présentation des informations tête haute ou tête basse montés sur les tableau de bord,

2°/ sur les dispositifs de présentation des informations par dispositifs montés sur casque.

En ce qui concerne les dispositifs montés sur le tableau de bord et la charge de travail des équipages, Monsieur MORRIS A. OSTGAARD a présenté de façon saisissante des progrès réalisés dans le guidage et le contrôle des avions grâce à l'utilisation des microprocesseurs et en particulier : l'amélioration des performances atteintes par les nouveaux avions à commandes électriques, leur maniabilité et l'apparition de performances nouvelles (possibilités d'accélérations latérales avec changements d'altitude et la ligne de vol sans changement d'assiette). Il a été intéressant de noter au passage que toutes les phases de vol ne bénéficient pas de la même manière de ces nouvelles techniques.

Monsieur R.H. HOLMES s'est attaché plus spécialement à la disposition des commandes et la présentation des informations sur écran de télévision. Il a montré que l'on pouvait diminuer le temps d'accomodation oculaire et simplifier le choix des informations nécessaires à telle ou telle phase de vol en les présélectionnant et les collimatant. Il a aussi montré la faisabilité actuelle des écrans de télévision en couleur ayant les caractéristiques requises pour être utilisés en vol, et les bénéfices que l'on peut attendre de ce perfectionnement dans la diminution de la charge de travail des équipages.

En ce qui concerne les dispositifs montés sur casques, Monsieur D.N. JARRETT a étudié la gêne apportée par les mouvements relatifs du casque et de la tête au cours des accélérations et vibrations rencontrées au cours du vol à basse altitude et grande vitesse. Il a montré qu'en augmentant la brillance des informations on pouvait diminuer la gêne apportée par ces mouvements.

Madame Gloria TWINE CHISUM, grâce à son expérience étendue dans ce domaine, a montré tour l'intérêt de ces dispositifs sur différents types d'appareils et pour différentes phases de vol. Elle a indiqué les axes de recherches qui doivent faire l'objet d'effort : choix des symboles, de la taille des lettres et chiffres, du contrôle automatique de leur brillance, de la distance de projection, de l'angle visuel couvert par ces informations et développement d'un système binoculaire.

Le Professeur M.L. WOLBARSHT a enfin dressé un tableau des différentes recherches sur la vision entreprises sous l'impulsion de l'U.S. Navy, à la fois dans les domaines fondamentaux et les domaines appliqués.

En conclusion, cette session a montré qu'en raison des bénéfices attendus dans l'allégement de la charge de travail des équipages, il était de la plus haute importance de poursuivre les efforts entrepris dans la présentation des informations par écran de télévision, notamment en coleurs. Elle a aussi montré que les dispositifs montés sur casque pouvaient être considérés comme un dispositif d'avenir, et peut être comme une solution pour les avions à haute performance pour assurer, sans trop de problèmes techniques, le pilotage sur siège basculant ou avec dossier très incliné.

Part V. Escape and Survival (Dr Sarah A. Nunneley)

We have seen that high-speed, low-level flight presents tremendous challenges in the area of escape and survival. In particular, benefits can be gained from the analysis of past experience with escape and ejection, and also computor modelling is a very useful technique. We have seen the very great extent to which realistic training can contribute to certain types of survival for example, following ditching. However, in the high-speed, low-level mode, especially over land, it appears that maximal automation of the escape processes will be advantageous. Of course the real problem here is how to prevent completely any mistaken actuation of these systems, such as the disengagement of the parachute harness, or, if it is ever possible, to approach the problem of automatic initiation of ejection. We were told today of the problem of keeping the pilot unwillingly in the aircraft after he had decided to leave; I think it would be considerably worse to find yourself leaving the aircraft when you would prefer to remain. We have seen that there are a number of different approaches to these escape problems and I think it would be good if we can eventually come to a consensus among our different laboratories and nations as to how best to solve these problems. In doing so it seems to me that we need to keep in mind that sometimes our priorities change when we consider two very different conditions: escape and survival in peacetime and training, as opposed to escape and survival in wartime. While I am not an expert in this particular area, I wonder for instance, when we are eliminating some of the equipment that the man carries with him because we have very rapid pick-up, particularly from the sea, whether in wartime we may rather suddenly find that our pick-up is not so quick. Similarly, I can see some disadvantages to being rocketed to a considerable height and then floating slowly downwards over enemy territory. In conclusion I think that this session has pointed out that there are considerable grounds for continuing discussion on this topic, and I hope we will see this happen in the future.

*Editor's note:

Summaries for parts II and V are tape transcripts edited by the session organiser: those for parts I, III and IV have subsequently been rewritten by the individual chairmen.

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14. Abstract

Recent developments in radar and missile systems indicate that high-speed flight at low-levels offers the optimum means for reaching targets deep within defended territory while, unfortunately, imposing considerable physical and mental stresses on the aircrew.

The 22 papers presented by experts within the compass of Guidance and Control, Flight Mechanics and Aerospace Medicine discussed the effects of ride quality, physical environment, temperature, vibrations as well as the requirements for cockpit design escape and survival in low-level, high-speed flight.

Recommendations were put forward for improvements in systems management techniques, modifications to existing systems and design of new ones in order to enhance the performance of the man and the system and improve the chances of survival of both in this demanding operational environment by reducing the workload imposed on the aircrew.

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